The Effectiveness of Working Memory Training on Classroom-Related Attention

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The Effectiveness of Working Memory Training on Classroom-Related Attention

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Abstract

The role of working memory (WM) in disorders of attention and learning is well established in the literature, some suggesting that low working memory may be a core deficit in AD/HD. As such, computerized cognitive interventions to improve WM have been developed and shown promise by demonstrating training effects such as improved attention and fluid reasoning. However, debate continues as to whether adaptive training leads to improvement on non-trained tasks. Little research has demonstrated improvements that generalize to "real life" WM or attention. The current study examined the effectiveness of WM training on real-world attention performance. Participants included 15 children, ages 6-15, identified as having learning and attention problems. Both before and after completing 5 weeks of WM training, each child was assessed via the Virtual Classroom Continuous Performance Task, a validated measure of sustained attention set within a virtual environment. Results suggested that WM training led to substantial improvements in sustained attention in a real life scenario (classroom learning). Observing such improvements on ecologically relevant measures of attention adds to the discussion that computerized WM training may be a viable option to treat attention disorders.

The Effectiveness of Working Memory Training on Classroom-Related Attention

Attention Deficit-Hyperactivity Disorder (AD/HD) is one of the most prevalent behavioral disorders of childhood, affecting approximately between 8-9% of children ages 3-17 (American Psychiatric Association, 2000). Children diagnosed with AD/HD often experience academic and relational problems early in life and, as a result, are often diagnosed with secondary depression and/or anxiety (Barkley, 2006). Traditionally, behavioral interventions designed to ameliorate symptoms of AD/HD, including impaired attention, impulse control, and working memory, show little efficacy unless paired with psychostimulant medication (e.g. Pelham et al., 2000). However, research supporting a computerized cognitive training intervention has grown in the last ten years. These non-pharmaceutical interventions, aimed at improving cognitive skills such as working memory and attention, have been shown to not only improve performance on non-trained working memory tasks but also improve attention and non-verbal reasoning in samples of children with AD/HD (see Klingberg et al., 2005). As such, advancements in computerized cognitive training may offer a potentially invaluable resource in the treatment of AD/HD while also underscoring the importance working memory, a cognitive skill that, when improved, may facilitate greater behavioral outcomes in children with AD/HD.

Working Memory: An Overview

According to De'Esposito (2007), working memory "refers to the temporary retention of information that was just experienced but no longer exists in the external environment, or was just retrieved from long term memory." In his view, these internal representations of information can be short-lived, but may also be stored through active

maintenance. Information, in this way, is held online in an active manner until it is either rehearsed so significantly that it is retained in long term memory, or allowed to decay and thus ceases to exist in consciousness. According to Klingberg, the lead researcher behind Cogmed ™ Working Memory Training, working memory (WM) can be best described as “the ability to keep and manipulate information online for a brief period of time” (website). More formally, working memory is the cognitive system responsible for maintaining a short-term store of information available for further processing (Becker & Morris, 1999). The latter of these definitions is important because it highlights the ability of the working memory systems to use and manipulate information for the purpose of directed behavior. Persons utilize working memory for a host of important cognitive activities, such as reading comprehension, controlling attention, and problem solving. Tasks that involve working memory typically require active goal-directed rehearsal or manipulation of information; that is, it is irrelevant whether or not information is stored after processing by working memory unless it is used or retained to reach a goal or carry out a behavior. It is no surprise that working memory is often assumed to overlap other cognitive domains such as executive functioning and attention and plays a vital role in maintaining focused behavior in practical situations (Kane et al., 2007). Further, working memory processes are directly affected by extraneous interference or distractions and some argue that WM capacity is reflected in the ability to resist external distracters (Engle, Tuholski, Laughlin, & Conway, 1999).

It is well established that working memory has limited capacity. Early working memory researchers tended to view the construct as relatively static and typically constrained to seven pieces of information at once (e.g. Miller, 1956). However, evolving

research on brain plasticity, most salient in the prefrontal cortex, has prompted the field of cognitive neuroscience to reevaluate the limitations once put on WM capacity. Cognitive strategies, such as “chunking,” are known to improve WM capacity and retention (Gabriel & Mayzner, 1963). Developmentally, working memory capacity increases with age, in conjunction with the development of the prefrontal cortex, until around age 15, at which the capacity is roughly three times greater than that of a 4 year old (Gathercole, Pickering, Ambridge, & Wearing, 2004). Although typically static through adult life, WM capacity declines throughout older adulthood (Park et al., 2002).

Working memory capacity has important correlates in everyday life. It has been shown to be the single best predictor of intellectual functioning and may account for 50% of the differences in non-verbal IQ (Conway, Kane, & Engle, 2003). As a result, working memory capacity in childhood is an effective predictor of later academic attainment (Gathercole, Brown, & Pickering, 2003). Reading and math ability have also been linked to working memory capacity (Gathercole & Pickering, 2000; Geary, Hoard, Byrd-Craven & De Soto, 2004). It is no surprise that the improvement of working memory through intervention has received significant research attention over the past decade.

In the most general sense, the concept of working memory arose in response to the shortcomings of theories of short-term memory (STM) which traditionally refer to the temporary storage of information (Atkinson & Shiffrin, 1968). The main criticisms of STM stemmed from observations from Baddeley and Hitch (1974) who asserted that short term memory processes are not passive but involve manipulation and active engagement to be effective. In their influential model, Baddeley and Hitch outline a multi-component system in which three components function together dynamically. The

central executive (CE), an attention-like system with limited capacity, oversees two sub-systems; the phonological loop and visuo-spatial sketch pad. The central executive is crucial in the integration and delegation of information to each sub-component and is especially active when a task becomes cognitively demanding, such as carrying out simultaneous tasks or temporarily activating long-term memory (Baddeley, 1986). The phonological loop stores language information and has two subcomponents; a passive store which is associated with speech perception and an active store of articulatory, or speech production, information. In support of this component, Baddeley's (1975) found that WM span is larger for short words than long words due to time restrictions on the memory span. This finding is evidence of a timed-based rehearsal loop in the articulatory control system. The third component, the visuo-spatial sketch pad, is used in the temporary storage and manipulation of visual information, though others have argued that the visuo-spatial sketch pad should be considered to have two sub-components which store visual (form and color) and spatial information separately (Logie, 1995). Baddeley (2000) later added a fourth component, the episodic buffer, which is able to integrate combinations of visual and verbal information into a unifying, multi-dimensional representation.

Although Baddeley's model is widely accepted and typically operationalized as the primary definition of working memory in cognitive psychology, other models have surfaced which provide alternative hypotheses on how the brain actively uses and retains stored information. Cowan's (1995) cognitive theory describes working memory as an activated retrieval stage of long term memory (LTM). This theory proposes two levels of WM; the first that consists of active LTM representations and the second that focuses

one's attention on up to four representations that are held in consciousness. In this way, the contents of WM are not stored, per se, in an active storage buffer, but are rather the "subset of information that is within the focus of attention at any given time" (De'Esposito, 2007). Similarly, Ericsson and Kintsch (1995) argue that working memory should not be considered its own construct but is simply a part of the LTM retrieval process. Named the "Long Term Working Memory" model, they posit that working memory simply holds cues to activate specific retrieval structures of LTM. Such theories support the overlap of working memory and other cognitive abilities, such as attention.

Recently, theorists have focused on individual differences in working memory capacity in an attempt to explain impaired performance on WM tasks. In this vein, Unsworth and Engle (2007) proposed a dual-component model of working memory which posits that low WM arises from deficiencies in either a dynamic attention component (primary memory or PM) or a probabilistic cue-dependent search component (secondary memory or SM). Thus, poor performance on WM tasks is assumed to be the result of inability to maintain information in the PM and poor retrieval of relevant information from the SM.

How Working Memory is Measured

Traditionally, working memory has been measured by neurocognitive assessment. Span tasks, which include counting, operation, visual, and reading spans, are the most widely used assessments of working memory and have held up over time as reliable and valid (Conway et al., 2005). Theoretically, span measures were initially based on Baddeley's (1974) model in that they were created not only to demonstrate the ability to store and rehearse small amounts of information but also simultaneous manipulation,

processing, and addition of more information. Whereas the first span task required the reading of short sentences to assess the retention of language information, Turner and Engle (1989) subsequently demonstrated that WM capacity could be assessed with information that was not specific to the domain of interest. For example, the use of operation and counting spans estimate overall WM ability by generalizing WM performance on a subset of directions or number to gross WM functioning. Over time, the evaluation of reliability on WM span tasks has been adequate, ranging from .7-.9 for counting spans (see Cowan et al., 2005). In terms of validity, the evidence presents an uncertain picture. WM span tasks have been shown to be correlated with a host of other cognitive abilities, including attention, perception, and distracter resistance, inhibition, and other executive skills, suggesting a lack of divergent construct validity, albeit highlighting the influence of WM in general cognitive ability. However, research also has supported construct validity in that WM spans *do not* predict performance on tasks that reflect automatic processing. In this regard, WM span tasks differ from "simple" span tasks (that is, span tasks that do not require a manipulation component) by uniquely showing predictive power for complex cognition (see Kane, Bleckley, Conway, & Engle, 2001). Overall, span tasks have utility in the accurate assessment of generally working memory ability.

Neurophysiology of Working Memory

It is widely known that the hippocampus and other limbic system structures play a large role in memory functioning (Kolb & Wishaw, 1998). However, early research on primates differentiated between working memory systems and neural systems responsible for short and long term memory; primarily in the prefrontal cortex (Jacobson, 1938). It

was shown that damage to the prefrontal cortex prohibited monkeys from remembering the spatial location of objects after a short delay. Moreover, Fuster (1973) demonstrated that neurons in the prefrontal cortex continued to fire during a delay period in which monkeys were required to remember the location of food, indicating that this region was responsible for representing the location of the stimulus when not in sight. Such studies illustrate the importance of maintaining the representation of information within these systems between exposures to a stimulus. Recent findings have pointed to the temporal limits of working memory; showing that over time, representations decay (Ashby, Ell, Valentin, & Casale, 2005).

With advances in neuroimaging technology, researchers have sought to understand the localization and functional neuroanatomy of working memory. Although early research had implicated the prefrontal cortex as the primary neural substrate of working memory, functional imaging has only recently uncovered the complex and interconnected neural systems that generally extend throughout cortex, including the dorsolateral prefrontal cortex and posterior parietal regions (see review by Smith & Jonides, 1999). The most important distinction has been the identification of separate neural systems modulating spatial and verbal information. With the aid of Baddeley's (2000) multicomponent model, Muller and Knight (2006) have highlighted these differences by using fMRI to show that specific spatial tasks, as carried out by the visuo-spatial sketchpad, are processed through both the ventral stream of the occipito-temporal cortex and the dorsal stream of the occipito-parietal cortex, implying that spatial operations are more heavily weighted than executive processing tasks of the prefrontal cortex. Further, they argue that verbal WM tasks, operated by the phonological loop, are

processed through areas of speech production, such as Broca's area. Despite this evidence, research has been consistent in demonstrating an integrated processing system between frontal and parietal lobes, albeit distinct within the verbal and spatial domains. Most would agree that some level of sustained activity for maintenance is found in the prefrontal cortex during WM tasks while focal language and spatial areas assist in domain-specific processing of verbal and spatial information, respectively (Curtis & D'Esposito, 2003).

Neurochemically, dopaminergic transmission in the prefrontal cortex is known to have a significant role in working memory, primarily modulated by D1 receptors (see Muller, von Cramon, & Pollman, 1998; Sawaguchi & Goldman-Rakic, 1991). Further, evidence for a frontotemporal dopaminergic network involved in WM has been demonstrated by Aalto and colleagues (2005), suggesting that these brain regions, secondary to the prefrontal cortex, may play a role in working memory functions. Studies on the training of working memory and its effect on dopamine functioning give promising evidence to the plasticity of neurochemical systems involved in WM (see McNab et al., 2009).

Working Memory and AD/HD

Attention Deficit/Hyperactivity disorder is a common neurobehavioral disorder that has traditionally been thought to comprise symptoms of impaired sustained attention and hyperactivity/impulsivity (American Psychiatric Association, 2000). These behaviors typically begin before the age of 7 and persist throughout development, occasionally into adulthood (Barkley, 1997). As is such, AD/HD is associated with problems in school, poor social relationships, early substance abuse, and has high comorbidity rates with

depression and anxiety (Barkley, 2006). Thus, early identification and treatment of AD/HD, typically with stimulant medication, is of great importance. Recent research has begun to look beyond traditional understandings of the AD/HD symptom constellation and has identified poor working memory, a specific characteristic of general executive dysfunction, as a core deficit within this disorder (Castellanos & Tannock, 2002). For instance, Rapport and colleagues (2008) found AD/HD children to have impaired working memory across all three components of Baddeley's (2000) model. AD/HD children and adults have also been shown to have significantly poorer performance on complex working memory tasks than controls, implying that higher levels of distractibility creates greater difficulty in resisting irrelevant and interfering stimuli, thus impairing WM capacity (Englehardt, Nigg, Carr, & Ferriera, 2008). Most compelling, a meta-analysis of AD/HD studies found both verbal and visual WM impairments in both children and adolescents with AD/HD when compared to controls (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005). Children with AD/HD also demonstrate characteristically slower and less accurate reading fluency than typically-developing peers. Jacobson and colleagues (2011) hypothesize that working memory mediates the relationship between processing speed and reading in this population, suggesting that a deficit in executive control and WM, not the orientation of attention, is culpable. With such evidence, one could reasonably speculate that consequent behavioral deficits characteristic of AD/HD, such as problem solving, organization, and forgetfulness, may be attributed to deficits in working memory.

The noted WM deficits in children with AD/HD may be linked to the observed overlap in WM and attention systems in the brain. Whereas prevailing models of working

memory utilize a controlled attentional function in the maintenance of information in one's mind (e. g. the central executive), neuroimaging studies have recently demonstrated the shared neural systems of these cognitive domains, specifically in the activation of the prefrontal cortex and posterior parietal cortex during maintenance of a working memory representation, as well as a spatial attention task (Ikkai & Curtis, 2011). Behaviorally, Kane and colleagues (2007) found that individuals with lower working memory capacity endorsed significantly more mind wandering and off-task thoughts during cognitively demanding activities in everyday life than their peers with high working memory capacity. As described by Klingberg (2010):

> Attention is thus closely linked to WM. Controlled, or top-down, attention refers to the voluntary allocation of selective attention and relies on parietal and prefrontal regions that largely overlap with activation during WM tasks in both the parietal and prefrontal cortex. Control of attention is necessary in WM tasks, for example when selecting only relevant information. (p. 318)

Intervention Through Computerized Cognitive Training

In 1999, Torkel Klingberg of the Karolinska Institute in Stockholm initiated the first research proposal to examine the effects of working memory training in children with AD/HD. The program used in the current study, named Cogmed ™ RM, is reflective of typical "brain training" programs that emphasize both discoveries in cognitive neuroscience as well as modern, interactive technology that would appeal to child users. The structure of WM training is relatively simple: a computerized platform offers home-based training which consists of an array of adaptive and intensive cognitive exercises tailored to the WM capacity of the user. Exercises cover both visual and verbal WM

domains with slight variations and difficulty levels. The particular intervention chosen for the current study, Cogmed ™ RM, employs a highly supportive training structure which includes feedback from a one-on-one coach and training aid to ensure compliance and motivation throughout training. Additionally, child trainees and their families benefit from comprehensive education on the role of WM and its correlates in everyday behavior. This variable begs the question of whether interpersonal interaction contributes to the observed training effects and documented positive outcomes.

Whereas most cognitive training programs typically reflect the lucrative big business of brain training without dedicated empirical support, a new wave of programs have proclaimed to represent a new breed of “evidence-based” cognitive training. The history of empirical support for cognitive training began in 2002 when Torkel Klingberg and his research team published the first double blind, placebo controlled study to examine the effects of working memory training in children with AD/HD. Initial results were promising as the experimental group showed greater improvements on both trained and non-trained working memory tasks, as well as improved fluid reasoning. Follow up studies by Klingberg’s team (2005) demonstrated that increases in working memory capacity not only improved performance on post-training assessments but affected real world behaviors as parents’ ratings of AD/HD symptoms significantly decreased after training. Expanding on initial findings, independent researchers sought to replicate the promising results with samples of AD/HD children, citing the potential to improve attention due to its similarities in neural substrates with working memory. Beck, Hanson, Puffenberger, Benninger, and Benninger (2010) found WM training to improve AD/HD symptoms, such as inattention, executive dysfunction, and parent ratings of impulsivity

and hyperactivity. Several other independent research teams have found similar training effects (see Holmes et al., 2010; Mezzacappa & Buckner, 2010).

Another important finding of early WM training research centers on neurophysiological changes after training. Oleson, Westerberg, and Klingberg (2004) used fMRI technology to examine changes to neural activation patterns in participants after WM training. They found that, after completing training, healthy adult subjects displayed greater activation in the right medial-frontal gyrus and inferior parietal cortex during WM tasks; areas associated with working memory functioning. Further, McNab and colleagues (2009) examined the effects of training on dopaminergic systems implicated in working memory, finding training-related changes in D1 receptor binding density supporting increased dopaminergic efficiency and demonstrating a strong relationship between WM training and neurochemical plasticity.

Other applications of explicit WM training have been observed in the fields of educational psychology, rehabilitation, and gerontology (e.g. Dahlin, 2011; Brehmer, Westerberg, & Backman, 2012; Lundqvist, Grundstrom, Samuelsson, & Ronnberg, 2010). Researchers continue to examine whether WM training improves learning outcomes in the classroom, whether training may be viable in the amelioration of age-related cognitive impairment, and if training can improve WM impairments after brain injury.

Transfer Effects

A general problem in early cognitive training research is the observed lack of generalization from improvement on a trained task to improvement on non-trained tasks. Of even more concern, previous studies have yet been able to demonstrate lasting effects

after training. Decades of cognitive training research has established that repeated performance on a task will always lead to improved performance on the trained task (Klingberg, 2010). When a person's training task is similar to the outcome measure on which they will later be tested, it is difficult to determine whether the training has had a true effect on cognitive ability or if an improvement is the result of a practice effect. The most important question surrounding the improvement of cognitive abilities is not whether a skill can improve, but whether improvement on a task leads to improvement in a) real world functioning in that particular domain and b) improvement in both associated and non-associated domains.

Long ago, the field of cognitive psychology agreed on the ostensibly proven fact that little could be done to improve overall cognitive ability. In his theory of *identical elements*, Edward Thorndike (1906) proposed that improvement in one cognitive domain could only influence another domain if it related. In other words, the degree to which the learning task affects the transfer tasks depends on the how similar the tasks are. Expanding on this hypothesis, several taxonomies have been created to designate specific levels of transfer (Barnett & Ceci, 2002). For instance, if the training and transfer task are similar in nature, it would be considered *near* transfer. In contrast, dissimilarity in the training and transfer task would be designated as *far* transfer. Until the last decade, Thorndike's theory was widely unquestioned as research continued to demonstrate the relatively static properties of intelligence and academic achievement (see Jensen, 1969; Detterman & Sternber, 1982). However, strong evidence for the improvement of fluid reasoning through domain-specific training has caused theorists to re-examine the phenomenon of transfer. More specifically, several recent studies have demonstrated that

working memory training has led to improvements in fluid intelligence (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Klingberg, Forssberg, & Westerberg, 2002). Other demonstrations of transfer include domains associated with WM, including improved reading comprehension, math performance, and attentional control (Holmes, Gathercole, & Dunning, 2009; Beck et al., 2010). Although such findings appear to contradict a long history of cognitive training research in which generalized improvements were ostensibly absent, the current cognitive training paradigm utilizes two critical components that have been noticeably absent in previous research designs: a) intense, demanding level of difficulty in training over a long period of time, and b) an individualized, adapted protocol in which the level of difficulty is customized to fit the trainee's optimal challenge point. Such differences in training paradigm appear to account for the discrepancy in transfer effect sizes found in early research. As a result, the volume of new training programs is currently growing at a rapidly faster pace than research to support it.

Despite promising evidence for WM training as a viable intervention for an array of applications, it is paramount to critically scrutinize the existing evidence and identify the limitations of cognitive training, in general. In a critical review of the literature, Shipstead, Redick, and Engle (2010) offer a compelling argument as to how existing WM training studies fall short. First, they argue that the ability for WM training to improve fluid reasoning, as hypothesized by several researchers, has not been consistently found across the literature. Second, in dissecting the criterion and outcome tasks, they assert that "higher scores" cannot sufficiently and solely be accounted for by working memory improvements as no task is "process-pure" (p. 268). Finally, no researcher has yet to

scientifically establish that general span scores adequately and fully represent the construct of working memory or whether such scores better relate to task-specific learning. Although the authors acknowledge that WM training may improve attention, it is clear that much more is to be learned about cognitive training.

In a meta-analysis of 23 studies that reported effects of WM training across several training platforms, Melby-Lervag and Hulme (2012) present a criticism of the claims made by intervention programs. The authors argue that, across the literature, WM training produces reliable short-term improvements of WM-specific skills with no near-transfer effects for verbal or visual WM observed after follow-up. They also noted that the analysis revealed no compelling evidence that training effects generalize to other cognitive abilities such as math, reading, or attention. Based on these findings, they asserted that WM training is useful for producing short-term, training related effects but offer no clinical relevance.

Improving Ecological Validity

The explosion of cognitive training products in the last decade has demanded evidence for generalizable effects from training. Individuals who train their working memory must see behavioral and functional improvements in everyday life for the intervention to be considered successful. Despite the preponderance of evidence that WM training leads to gains in fluid reasoning, academic ability, and a reduction in AD/HD symptoms as measured by standardized testing, there have yet to be conclusive results that reveal positive long-term outcomes. In response to these criticisms, some researchers have proposed new variations of working memory that speak directly toward its role in everyday functioning, for instance, the ability to remember and carry out a complex list

of instructions. Holmes and colleagues (2009) adapted this pragmatic representation of working memory to utilize cognitive training in a classroom setting among children with learning problems attributed to low working memory. As an outcome measure, the authors employed an instruction task similar to the follow: "*Touch the yellow pencil put the blue ruler in the red folder.*" They found that WM training led to improvement in the ability to carry out such tasks successfully, demonstrating that training may be beneficial in improving working memory tasks relevant to what is encountered in daily life.

Moreover, the integration of technology with psychological testing to improve ecological validity has already been established. The use of virtual reality provides an exciting medium to capture real-world behavior previously not possible with traditional cognitive assessment (e.g. Schultheis & Rizzo, 2001). Assessment within these virtual environments enables researchers to observe behavior in real life settings as opposed to a laboratory, adding a sense of being "present" within the environment and participants being less aware of the examiner (Baumgartner et al., 2008; Draeger, Prior, & Sanson, 1986). Further, Rizzo, Bowerly, Shahabi, and Buckwalter (2004) have demonstrated that virtual reality assessment provides increased levels of experimental control over traditional pencil and paper methods. Virtual reality also allows for standardized behavioral assessment via responses recorded by a head mounted display which tracks the participant's movements (Rizzo et al., 2002).

The need for validated outcome measures that approximate real world functioning is salient across research fields. As it pertains to the role of cognitive training in ameliorating inattention relating to AD/HD, this need is of paramount importance. Traditionally, AD/HD has been assessed through a variety of methods, often by

neuropsychological tools measuring sustained attention. The Continuous Performance Test (CPT), a preferred assessment method in which examinees respond to an identified stimulus presented variably and persistently amidst distracters over time, typically shows group differences between AD/HD and normal individuals (Denney, Rapport, & Chung, 2005). However, criticism has emerged surrounding the sensitivity of the CPT to identify poor attention (Adams, Finn, Moes, Flannery, & Rizzo, 2009). In response, Rizzo and colleagues (2000) developed the Virtual Classroom (VC), a continuous performance test embedded within a virtual environment which more accurately depicts a real-life setting than traditional designs. In this virtual scenario, the user must respond to stimuli as viewed on the chalkboard from his/her desk chair while resisting distraction typical of an academic setting (peers throwing paper airplanes, whispering, windows through which traffic can be seen and heard). Further, the VC allows for the measurement of head movements during the task; a variable known to be associated with hyperactivity (Teicher, 1996). Research using the VC has shown that children with AD/HD were attending to distractions on 25% of the missed target stimulus trials, whereas controls looked away during only 1% of the trials, demonstrating the potential for improved analysis of complex attentional performance (Parsons, Bowerly, Buckwalter, & Rizzo, 2007). Adams and colleagues (2009) found that the VC improved upon traditional CPT classification rates of AD/HD (87.5% vs. 68.8%). Additionally, children rated the VC as more enjoyable than the TOVA CPT (Pollak, Shomaly, Weiss, Rizzo, & Gross-Tsur, 2010). Thus, the Virtual Classroom has the potential to aid in the evaluation of the efficacy of cognitive training by approximating a scenario in which attention, working

memory, and executive abilities can be measured on par with what is actually experienced by the user in the real world.

Hypotheses

The current study examined the effectiveness of WM Training on Virtual Classroom performance in a sample of children with attention and learning problems. Participants were identified as having low working memory or attention and were administered a battery of tests, including the Virtual Classroom, before and after WM training. The hypotheses of the study were threefold: first, WM training would improve working memory on trained tasks. This was measured by the "index improvement," a measure of progress during training, calculated by a standardized performance average on an individual's three best training exercises. The index score on day three of training is subtracted from the highest index score on any particular training day (typically at the end of training) to produce the "index improvement," representing the actual statistical progress of the trainee on trained WM measures. Second, WM training would improve working memory performance on established, parallel non-trained span tasks; digit span (forward, backward, and total) and the working memory index (WMI) from the WISC-IV. These tasks were characterized as parallel due to the similarity between these measures on the specific WM training exercises on the intervention. Finally, WM training would improve performance on the Virtual Classroom CPT; specifically, there will be a significant difference between baseline and time 2 performance on the distracter condition which provides a real-world relevant sustained attention task. Improvement was measured by differences between baseline and time 2 performances on omission

errors, commission errors, hit variability, reaction time, reaction time variability, and head movements during the task (as measured by the head-mounted display).

Method

Participants

The current study included 15 participants (12 boys) between the ages of 6 and 13 (*M* = 8 years, 11 months). All 15 of these participants were right handed. The participants varied in ethnicity with 53% Caucasian, 20% African American, and 27% Asian/Pacific Islander. Children in the participant group were initially recruited from the emerging needs (EN) program in a Southern California private elementary school. This program is designed to identify and support the unique learning and attention needs of students. Recruitment was conducted with the assistance of the EN coordinator at the private school who sent letters to the families of qualified students informing them that their child was eligible for the research study based on enrollment in the EN program. General flyers were also disseminated at the school allowing families to contact the EN coordinator to inquire about eligibility. It should be noted that several participants initially recruited into a control group as part of a larger study were later assigned to the experimental group and offered the cognitive training intervention due to significantly low attention and/or working memory scores on standard neuropsychological assessment tools. These classifications were made by case conference with a license neuropsychologist. After exhausting this pool, a second phase of recruitment drew participants with similar learning and attention problems from clinical networks in the community. All participants were screened for and not included in the study if they had been diagnosed with a previous or existing neurological, physiological, or psychiatric

disorder. No monetary compensation was provided to participants although each child received a small prize after each testing session and each family was provided feedback via an abbreviated research report of findings based on neuropsychological testing performance with highlighted strengths and weaknesses.

Measures

Virtual Reality (VR) Classroom Experimental Task. The Virtual Classroom (VC) was administered to all participants at both phase 1 and phase 2. The Virtual Classroom is a Head Mounted Display (HMD) Virtual Reality system for the assessment and possible rehabilitation of attention processes and is specifically designed to measure sustained attention, impulsivity, and distractibility. This scenario has evolved from a research application into a more advanced prototype that has undergone initial standardization testing. The VC was given on a Pentium 4 level laptop computer with 1 GB RAM and a 128 MB DirectX 9-compatible NVIDIA 3D graphics card. The HMD that was chosen was the eMagin z800, with displays capable of 800x600 resolution within a 40-degree diagonal field of view. Within the VC, each participant finds themselves sitting at a square desk in a traditional classroom containing adjacent rows of desks occupied by other students, a female teacher at the front of the classroom, a blackboard, and a large window to the left of the participant that looks out into a busy street. Within the virtual environment, participants experience common classroom distractions that can be controlled and manipulated to approximate a life-like classroom setting.

Each child is instructed to view a series of letters presented on the blackboard and to respond by hitting the spacebar on the keyboard only after observing an “X” preceded

by an “A” and to withhold responding in any other condition. The letters were presented at a rate of one every 1350 milliseconds and remained on the screen for 150 milliseconds. Although the VC can offer this continuous performance test with and without distractions, the current study utilized only the distraction condition of the test; lasting 10 minutes and being comprised of 400 stimuli. The distractions were as follows: pure auditory distracters (classroom noises), pure visual distracters (paper airplane flying across the visual field), and mixed auditory and visual distracters (a car “rumbling” by the window and a person walking into the classroom with hall sounds occurring when the door to the room was opened). Each distracter was displayed for five seconds and presented in randomly assigned intervals of 10-, 15-, or 25 seconds. A total of thirty distracters (10 different distracters, three of each) were included in the 10-minute condition.

Wechsler Intelligence Scale for Children, Fourth Edition. The WISC-IV was administered to each participant during both phase 1 and 2 (Wechsler, 2003). Only the working memory index (WMI) subtests were included in the analyses. Letter Number Sequencing requires the test taker to sequence a series of letters and numbers both sequentially and in alphabetical order after hearing them in a randomized fashion. Similarly, the subtest Digit Span asks the test taker to listen to a string of numbers and then to repeat it either forward or backward. Digit Span scores are calculated for number of digits forward, number of digits backward, and total cumulative score. Reliability coefficients for Letter Number Sequencing and Digit Span are .90 and .87, respectively. The total Working Memory Index, a composite, age-corrected score that includes both subtests, has a reliability coefficient of .92 and Chronbach’s alpha of .71.

Procedures

The current study was divided into two phases. In phase one, participants were administered a pre-intervention neuropsychological evaluation consisting of both standardized assessments and the Virtual Classroom task. Prior to phase 1, parents gave informed consent for their children to participate in the study and each child gave oral consent after receiving explanation of the procedures. Participants and their parents were informed that they did not have to complete the testing if so desired and could withdraw at any time. The testing battery was administered by graduate assessment clerks and completed in several shorter sessions; up to but no more than 3 hours. Administration was conducted at the EN center of the recruitment school or in the neuropsychological research laboratory at Fuller Theological Seminary. Additionally, parents and teachers were asked to fill out several behavioral rating forms in addition to parent's providing demographic information and developmental history.

Directly following the initial assessment, participants were invited to transition into phase 2 which consisted of Cogmed ™ Working Memory Training and a post-intervention assessment approximately 10-12 weeks after completion of the intervention. Upon completion of phase 1, participants and their families met with the qualified Cogmed ™ Coach on the research staff to begin the intervention. An explanation and description of Cogmed ™ from their website is provided below.

> The Cogmed ™ training method consists of 25, computerized training sessions, each 30-45 minutes long. Each session consists of a selection of various tasks that target the different aspects of working memory. The training is done on a

computer at home, in school, or at work. The training program is five weeks long with five sessions every week. It is a rigorous program designed to improve working memory through intensive and systematic training. The training is available through professional channels around the world. The training is always led by a Cogmed ™ Qualified Coach who works with the user to provide structure, motivation, and feedback on the progress. The program is challenging and rewarding, and for the best possible training effects, sustained effort is necessary. This is why there is always a Cogmed ™ Qualified Coach involved. The Cogmed ™ network of professionals has a proven track record of providing clients with excellent support and results. The complete program includes:

Initial Interview – The Cogmed ™ Qualified Practice schedules a talk with the person interested in going through the program (or the parent if it is regarding a child). The likelihood of him/her benefiting from the training is evaluated.

Start-up session – The Cogmed ™ Coach plans and structures the training together with the user/family. During the first session, the user is oriented to the training program and is able to try different exercises within the program's "test" condition. The user and family also formulate specific goals for training and outline a 5-week reward system in which the user is rewarded after each week of training. Typical rewards include play dates, frozen yogurt with the family, or choosing a movie to watch.

Five weeks of training with weekly coach calls – The user is training at home and talks with the Cogmed ™ Coach on a weekly basis to get advice on how to get the most out of the training, hear feedback, and increase motivation. Coach calls can

also include analyzing data from training, suggesting optimal break times during training sessions, and copious positive reinforcement to ensure compliance.

Access to the Cogmed ™ Training Web – Both the user and the Cogmed ™ Coach review and monitor the results of each day's training, using an online system. The coach monitors training data throughout the week and before coach calls. The data includes charts to track progress on each exercise, break downs of each trial of each exercise for every day trained, and an overall aggregate training , called the "index improvement," which is calculated by the difference between a user's performance over the first three days of training and their best training day.

Wrap-up session – At the time of phase 2 testing, the Cogmed ™ Coach summarizes the training together with the user and provides feedback data from the Cogmed ™ Training Web.

Six months follow-up interview – The Cogmed ™ Coach documents training effects again, with more time elapsed and the effects fully emerged.

Cogmed ™ Extension Training – When the intensive five week training is completed and the training has been wrapped-up, the user gets access to 100 sessions of training with the software, to use over a 12 month period. Cogmed ™ Extension Training is optional and no extra fee involved for the first 12 months.

Approximately 10-12 weeks after completing Cogmed ™ training, participants were administered an identical assessment battery to phase 1.

Results

Initial Analysis and Demographics

Means and standard deviations of demographic variables were calculated, including age at testing, time elapsed between pre and post-testing, estimates of Full Scale IQ, and a measure of WM training progress labeled the “Index Improvement” (refer to explanation in hypotheses section). See Table 1 for complete descriptive analysis.

The current sample was comprised of 12 boys and 3 girls. Although 15 participants completed the WM and pre/post assessments, subsequent analysis of non-trained tasks utilized alternative combinations of the total participant group due to invalid protocols or missing data. Specifically, two participants were not included in the VR Classroom data analysis due to non-compliance with task directions (extremely high numbers of commission errors, rendering the protocol invalid), and two participants were omitted from the WM measure analysis due to missing data.

Working Memory Measures

Hypothesis #1 was addressed by averaging the index improvement recorded for each participant by the WM intervention. The current sample improved on an aggregate score related to progress on trained exercises over the entire course of training by an average of 25.4 units (SD=9.11). In comparison to mean data of index improvement provided by Cogmed ™ Working Memory Training (ages 6-16 average is “27 units, with a large normal range of 13-39 units”), the participants demonstrated typical improvement on trained working memory tasks. Index improvement was also examined as a covariate of other demographic variables and found to be negatively correlated with age based on Pearson product-moment correlational analysis.

To address hypothesis #2, performance on various non-trained, parallel measures of working memory were analyzed using paired-samples t tests (see Table 2). Consistent with the literature, Working Memory Index (WMI) subtests from the Wechsler Intelligence Scale for Children, 4th Edition, were used. The Digit Span subtest was divided into separate variables, forward, backward, and total score, in order to isolate components of WM (i.e. registration vs. manipulation). Analyses revealed performance differences between time 1 and time 2 testing in the direction hypothesized for several measures including Digit Span Backward, Digit Span Total Score, Letter Number Sequencing, and the Working Memory Index Composite (a combination of Digit Span and Letter Number Sequencing). Of all non-trained WM tasks analyzed, only Digit Span Forward was found to be non-significant but trending in the direction of the hypothesis. Both raw and scaled scores were analyzed to correct for performance differences related to age and cognitive development. To further control for age and other demographic variables, Pearson product-moment correlations were conducted between demographic variables and calculated difference scores on WISC-IV measures (i.e. time 1 testing score subtracted from time 2 testing score). In general, variables such as age, time elapsed between testing, IQ, and progress on the WM training intervention were not correlated with outcome measures. One exception was noted; IQ and time elapsed between testing were shown to be correlated with differences in performance on Letter Number Sequencing. Additionally, effect sizes for mean comparisons were conducted using Cohen's *d.* Moderate effect sizes were observed for significant variables and ranged from .56-.72.

Virtual Reality Attention Measures

To address hypothesis #3, paired-samples t tests were conducted to examine the differences in performance on the Virtual Classroom CPT between time 1 and time 2 testing. Variables of interest included traditional CPT measurements such as omission errors, commission errors, and reaction time. Additionally, head movements were tracked during the task and recorded via the head-mounted display system. Head movement variables were represented in a range of angles across 3-dimensional axes and portrayed by the number of degrees moved across each axis. Larger numbers indicate greater angle change and more movement.

Results of paired-samples t tests showed significant mean differences between assessments on the following variables: omission errors, hit variability, reaction time, and reaction time variability (see Table 3). All other variables, including data on head movements during the task, were non-significant. To account for differences in performance related to age and cognitive development between assessments, demographic variables were compared to the difference scores on each VR Classroom variable using Pearson product-moment correlations. Generally, demographic variables, IQ, time between testing, and index improvement had no association with differences on VR Classroom performance from time 1 to time 2, with the following noted exceptions: a correlation between omission errors and IQ, and a correlation between hit variability and age. Effect size estimates for significant variables were calculated using Cohen's *d* and found to be moderate to strong, ranging from .55-1.05.

Discussion

The present study examined the effectiveness of computerized working memory training in a sample of children with learning and attention problems. The primary aim of

the study was to evaluate transfer of training effects to related cognitive domains, specifically attention. Unlike previous research that has relied on subjective report of behavior to evaluate transfer effects (e.g. Beck et al., 2010), the current study employed a standardized measure of attention in a virtual classroom environment with the intention of replicating an academic setting in which cognitive deficits and behaviors typical of AD/HD are often observed to be detrimental to learning (Loe & Feldman, 2006). In general, significant mean differences were observed on working memory and attention measures between pre and post testing, showing that the effect of WM training not only improved WM capacity but also generalized to sustained attention.

To date, no other researchers have attempted to measure working memory training effects by approximating real world functioning in a controlled virtual environment. Whereas the development of WM measurement to improve ecological validity, such as “Instruction Working Memory,” has been an objective of such intervention research (see Gathercole, Durling, Evans, Jeffcock, & Stone, 2008; Holmes et al., 2009), assessing cognitive functioning in virtual reality presents an opportunity for improved experimental control and may better capture training effects related to behavior in the classroom environment. Previous research aimed at improving classroom attention and behavior used teacher report as the outcome variable with mixed results (see Klingberg et al., 2002; Beck et al., 2010; Green et al., 2002). Further, teacher report forms are known to be discrepant from parent ratings and are typically unreliable (Murray et al., 2007). Virtual reality assessment eliminates the bias inherent in questionnaire assessment and instead offers a psychometrically sound estimate of a

child's behavior during classroom tasks that demand sustained attention (e.g. Schultheis & Rizzo, 2001).

The most novel component of the current study was to examine whether computerized WM training would improve real world, classroom-related attention. Whereas previous research using rating scales to measure transfer effects to AD/HD-related symptoms has been inconclusive, several studies have indeed observed significant far-transfer effects on paper and pencil measures of sustained attention, such as the PASAT (see Brehmer et al., 2012). In line with these findings, results of the present study show that, as hypothesized, several aspects of attention as measured by the Virtual Classroom CPT were significantly improved after WM training, including omission errors, hit variability, and reaction time. The observed training effects on this outcome measure suggest that children who received the training intervention were better able to sustain attention during a tedious and lengthy classroom activity. The particular condition of the CPT used in the current study included randomized distracters presented throughout the task (i.e. an interruption by the principle, flying paper airplanes in the subject's line of sight). Thus, it can be implied that subjects were better able to resist distractions and maintain focus on the target stimuli as a result of the training, consistent with research that shows WM capacity to be linked to the ability to resist distraction from irrelevant stimuli (de Fockert, Rees, Frith, & Lavie, 2001). Subjects also improved in the time it took to respond to each correct stimulus, suggesting an improvement in processing speed. An effect of general "video game-style" cognitive training on processing speed has been previously demonstrated (e.g. Nouchi et al., 2013) and is expected considering the design of the training intervention that rewards quick responding to stimuli.

Additionally, subjects demonstrated improved consistency in both accuracy and speed of responding across the entire task as measured by hit variability and reaction time variability (significant decrease in both). These findings are important due to the known characteristics of AD/HD performance on CPT tasks; typical response patterns show a decline in the percentage of correct responses and reaction time as a function of time from start to finish (Epstein et al., 2003). Early on in such a task, children with AD/HD can respond quickly and accurately but demonstrate slower reaction times and more incorrect responses as they are required to sustain this focus over a substantial period of time. As this performance pattern is a distinct feature of AD/HD, improvement on this task in a real-world, ecologically relevant environment is promising.

Interestingly, the present results did not yield significant differences in behavioral data using the precise measurement of head movements during the sustained attention task, contrary to existing research by Klingberg et al. (2002) that observed a reduction in head movements during assessment of children with AD/HD after WM training. This non-significant finding is likely related to the lack of statistical power in the current sample as approximately half of the subjects did not attain a recorded measurement of head movements due to technical difficulties during the computerized assessment. Despite this, the opportunity to measure off-task behavior via the head-mounted display presents a unique element to the assessment of AD/HD and should be included in future studies.

The current findings support strong existing evidence for AD/HD symptom improvement after WM training (see Beck et al., 2010; Holmes et al., 2009; Klingberg et al., 2002). A possible explanation for the observed near-transfer effect to attention relates

to the shared neural systems between working memory and attention. Neuroimaging has demonstrated the activation of matching regions of the prefrontal cortex and posterior parietal cortex during both maintenance of a working memory representation and completion of a spatial attention task (Ikkai & Curtis, 2011). Similarly, Oleson et al. (2004) demonstrated that WM training led to increased prefrontal cortex activity in these particular regions. Thus, it is conceivable that training-induced plasticity in WM areas of the brain also yield plasticity-related improvements in attention performance. Alternatively, training may not simply improve WM or attention as a corollary. As noted by Holmes and colleagues (2010), the intense and prolonged nature of the intervention may encourage the development of WM strategies that compensate for weaknesses in basic processes. Anecdotally, trainees tend to report using such acquired strategies in everyday life. However, this explanation does not account for the observed transfer effect to attention tasks, as the development of task-specific strategies, theoretically, should be applied only to tasks similar to training. If WM capacity is indeed increased through training-induced strengthening of neural substrates, it is difficult to determine whether the improvements in outcome are fully developed within the training protocol. Peripheral benefits (quality interpersonal experience with coach and parents, increased positive reinforcement, etc.) may also contribute to a heightened sense of self-efficacy and greater engagement with cognitively demanding tasks that lead to what Klingberg et al. (2005) call a positive feedback loop. This alternative and other similar explanations should be tested in future research by controlling for or at least measuring these additional training variables.

Consistent with hypotheses, subjects were shown to improve substantially on the actual WM training protocol via a built-in measure of training progress, a finding that is dependable across the literature (see review by Melby-Lervag & Hulme, 2012). This finding did not necessarily suggest that an increase in working memory capacity had been achieved, per se, but simply that the intensive practice on a particular cognitive exercise led to improved performance on that task. More importantly, a metric of training progress was useful to examine whether the quality of training or baseline levels of working memory capacity influenced the prediction of which subjects would improve on standardized neuropsychological measures of WM and attention. When using the index improvement as a covariate, it was found that younger trainees tended to demonstrate greater progress on training (i.e. higher levels achieved with respect to baseline capacity). This finding is consistent with what is known about working memory; that is, WM is an age-dependent cognitive skill that continues to develop into adolescence (Gathercole et al., 2004). With a sample that ranged in age from 6 to 15, it is not surprising to observe that age contributed to the variance in achievement on WM training in the current study.

Interestingly, it was observed that greater achievement on the WM training protocol did not lead to larger improvements on assessment performance between time 1 and time 2. In other words, gains on the training protocol were not associated with the magnitude of transfer effects observed on non-trained tasks. This finding is important because it implies that other characteristics or aspects of training were important in contributing to the variance in transfer effects. Simple improvement on the training protocol, as measured by the index improvement, was not enough to explain the statistical changes in working memory and attention performance on neuropsychological

measures. Thus, it may be hypothesized that alternate variables, such as interpersonal experience via supportive coaching or broader increases in self-efficacy due to accomplishing a large-scale task, may contribute to the mechanisms by which transfer effects are achieved.

In previous research on computerized WM training, traditional measures of working memory, such as the span-board or digit span tasks, have been categorized as “non-trained” tasks due to differences in stimuli, stimuli configuration, response mode (pointing and clicking the mouse vs. verbal response), and the testing situation (interaction with a person vs. the computer) between tasks (e.g. Klingberg et al., 2005). However, the identical task objective and the acquired familiarity by the participant is cause to reasonably expect practice effects on trained tasks of WM to apply to traditional measures (i.e. Digit Span Backward). Thus, the current study characterized traditional measures of WM as non-trained but parallel tasks, capturing the unique differences but similar characteristics between the trained tasks and outcome measures. Consistent with findings across the literature that WM training leads to improvements on closely related neuropsychological measures of WM (e.g. Klingberg et al., 2002; Klingberg et al., 2005; Holmes et al., 2010), the current study found that children who received WM training improved on both non-trained parallel and true non-trained WM tasks. Not only did participants significantly improve performance on an auditory digit span backward task, improvement was also observed on a measure of complex auditory working memory that had no resemblance to the trained tasks (WISC-IV Letter Number Sequencing). Thus, WM training appears to not only enhance performance on trained tasks, as expected, but also generalizes to non-trained WM tasks, a finding that suggests WM capacity can

indeed be improved despite the theoretical assumption that WM is highly heritable, static, and unaffected by environment (Engle, Santos, & Gathercole, 2008; review by Klingberg, 2012).

Limitations

A primary limitation of the current study is the small sample size, which restricts the generalizability of the findings and statistical ability to detect training effects. Further, the characteristics of the sample varied considerably in age and diagnosis. Although subjects were identified as having "learning and attention problems" by an educational specialist gleaned from previous psychoeducational testing data, many did not exhibit poor working memory upon enrollment in the study and, as a result, the mean working memory capacity of the sample was in the average range. However, subjects with a Working Memory Index in the normal range generally demonstrated a discrepancy between WM and other cognitive strengths. Results that demonstrate improvements in non-trained working memory measures after training do, however, support the idea that even individuals with normal WM capacity can benefit from training and experience transfer effects to other cognitive domains. This is consistent with findings from initial research on WM training (Klingberg et al., 2002).

Thus, the current findings generalize more broadly to a population of children with low WM, which is the typical target market for WM training. They may not generalize more specifically to groups of children diagnosed with AD/HD. Additional research is needed to substantiate the usefulness of using the virtual classroom CPT as a measure of training effectiveness with children specifically diagnosed with comorbid attention and working memory problems.

Furthermore, the lack of a control group also had the potential to limit the generalizability of the current findings and introduced possible inflation of observed effect sizes due to developmental and temporal variables. Although age-corrected scaled scores were used for traditional neuropsychological measures of WM to mitigate the statistical effect of age and development on performance outcomes, normative data was not available for the novel VR Classroom measure. However, a practice effect across testing time points was not believed to contribute to improvement on non-trained measures of attention given that CPT tasks are generally considered to have strong test-retest reliability and to be relatively unaffected by practice effects (Conners, Sitarenios, Parker, & Epstein, 1998). Furthermore, secondary analysis examined whether age was related to improvements between time 1 and time 2 assessments and found that raw score improvements were not influenced by age. Also in support of an authentic training effect is the finding that variability in time between testing did not drive the effect of the intervention on any outcome measure. This suggests that, while there may be some developmental change in performance (i.e. improvement on VR CPT simply by getting older), age does not explain the current findings. This finding also lends support to previous research that has found long-term durability of training effects (Chacko et al., 2013), as participants who completed the follow-up assessment 6 months or more after training demonstrated comparable effects of training on performance. It will be important to substantiate these findings with an age-corrected control or a normative sample.

Conclusion and Future Directions

The present study showed that intensive and adaptive training of WM may lead to transfer effects to associated cognitive domains including attention. The primary

implication of this main finding pertains to the viability of computerized WM training as an alternative treatment for children with ADHD. Previous research on WM training has called for evidence of improvements in real world functioning before cognitive training can be considered an effective solution for academic problems related to ADHD symptoms (e.g. Green et al., 2012). The present study builds on existing literature in two important ways. First, the findings offer support for WM training as a viable and potentially effective way to treat ADHD symptoms that, when untreated, can have devastating outcomes on classroom learning and achievement (Barkley, 2006). This approach may also provide an alternative for parents who are unwilling to expose their children to psychostimulant medication as a first line treatment for ADHD.

Second, the current study introduces a unique and ecologically relevant measurement tool to aid in the evaluation of new treatments for ADHD and learning disabilities. The growing field of computerized cognitive intervention is looking to novel methods of studying important developmental, cognitive, and learning constructs that closely resemble behavior in the real world. The VR Classroom offers one such novel measure. Future research using this task or any in-vivo measure should consider variables such as time on task and the systematic effects of distraction on overall attention performance. Without the limitations of traditional paper and pencil assessment in regards to generalizability of behavior, ecologically-relevant assessments such as the VR Classroom may help answer a crucial question posed by researchers: does WM training truly improve a child's ability to stay on task in the classroom?

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Table 1

Means and Standard Deviations for Demographic Variables

	n = 15	
Variable	*M*	*SD*
Age at Time 1 (months)	125.60	27.24
Age at Time 2 (months)	134.80	24.76
Time Between Testing (months)	9.2	5.19
Cogmed Index Improvement	25.4	9.11
Full Scale IQ (WISC-IV)	108.33	15.73

Note. Gender: 12 boys, 3 girls.

Table 2

Mean Differences on WISC-IV Working Memory Subtests, Time 1 and Time 2

	Time 1 (n = 13)		Time 2 (n = 13)			
Variable	*M*	*SD*	*M*	*SD*	$t(12)$	*d*
DS Forward Scaled Score	9.69	3.20	11.08	2.56	-1.64	*ns*
DS Backward Scaled Score	9.92	4.01	12.23	3.74	-2.38*	.60
DS Total Raw Score	14.62	4.27	17.69	4.31	-3.33**	.72
DS Total Scaled Score	9.92	3.77	12.00	3.62	-2.44*	.56
LN Raw Score	15.92	4.87	18.62	3.25	-3.09**	.65
LN Scaled Score	10.46	3.69	12.69	3.54	-2.67*	.62
WMI Composite Score	100.54	19.42	111.23	16.49	-3.04**	.59

Note. DS=Digit Span, LN=Letter Number Sequencing, WMI=Working Memory Index
*p < .05. **p < .01. ***p < .001.

Table 3

Mean Differences on Virtual Classroom CPT, Time 1 and Time 2

	Time 1 (n = 13)		Time 2 (n = 13)			
Variable	*M*	*SD*	*M*	*SD*	$t(12)$	*d*
Omission Errors	31.15	19.84	14.38	10.70	3.49**	1.05
Hit Variability	3.09	1.92	1.57	0.95	3.77**	1.00
Reaction Time (in seconds)	0.49	0.07	0.44	0.06	3.62**	.58
Reaction Time Variability	0.18	0.06	0.15	0.05	3.14**	.54
Commission Errors	28.23	15.90	26.69	20.76	.25	*ns*
RT to Commissions	0.51	0.08	0.50	0.10	.20	*ns*
Commission Variability	0.24	0.07	0.24	0.13	-.04	*ns*
A’	0.79	0.13	0.86	0.11	-2.03	*ns*
H’	-0.46	1.26	-2.06	4.97	1.13	*ns*
HM Yaw Range	5.04	3.47	3.17	3.49	1.35	*ns*
HM Pitch Range	7.56	5.13	8.01	7.03	-.18	*ns*
HM Tilt Range	3.94	3.10	4.55	4.84	-.35	*ns*

Note. RT=Reaction Time, A’=Measure of Sensitivity, H’=Measure of Specificity, HM=Head Movements Recorded by Head-Mounted Display.
*p < .05. **p < .01. ***p < .001.

Table 4

Correlations of Demographics and Difference Scores of Significant Findings, Working Memory Subtests

Variable	Gender	FSIQ	Time	Age1	Age2	II	DSB	DST	LN	WMI
Gender										
FSIQ	-.23									
Time Between Testing	.09	-.52								
Age (Time 1)	.22	-.02	-.45							
Age (Time 2)	.26	-.15	-.25	.98**						
Index Improvement	-.65*	.13	.36	-.58*	-.55					
DS Backward Raw Score	.08	.08	.15	-.31	-.30	.35				
DS Total Raw Score	-.13	-.18	.05	-.22	-.23	.45	.79**			
LN Raw Score	-.19	-.59*	.60*	-.19	-.06	.40	.07	.14		
Working Memory Index	-.22	-.45	.15	.01	.05	.46	.50	.77**	.61*	

Note. *$p < .05$. **$p < .01$. ***$p < .001$.

Table 5

Correlations Between Demographics and Difference Scores of Significant Findings, Virtual Classroom CPT

Variable	Gender	FSIQ	Time	Age1	Age2	II	Om	RT	HV	RTV
Gender										
FSIQ	-.28									
Time Between Testing	.30	-.23								
Age (Time 1)	.04	-.22	-.57*							
Age (Time 2)	.09	-.27	-.46	.99**						
Index Improvement	-.60*	.50	.07	-.59*	-.63*					
Omission Errors	-.29	-.61*	.19	-.07	-.05	.28				
Reaction Time (RT)	.11	-.05	.48	-.03	.04	.28	.31			
Hit Variability	-.43	-.56	-.24	-.55*	-.56*	-.17	-.58*	.05		
RT Variability	-.27	-.10	.32	-.20	-.16	.47	.42	.57*	.21	

Note. *p < .05. **p < .01. ***p < .001.

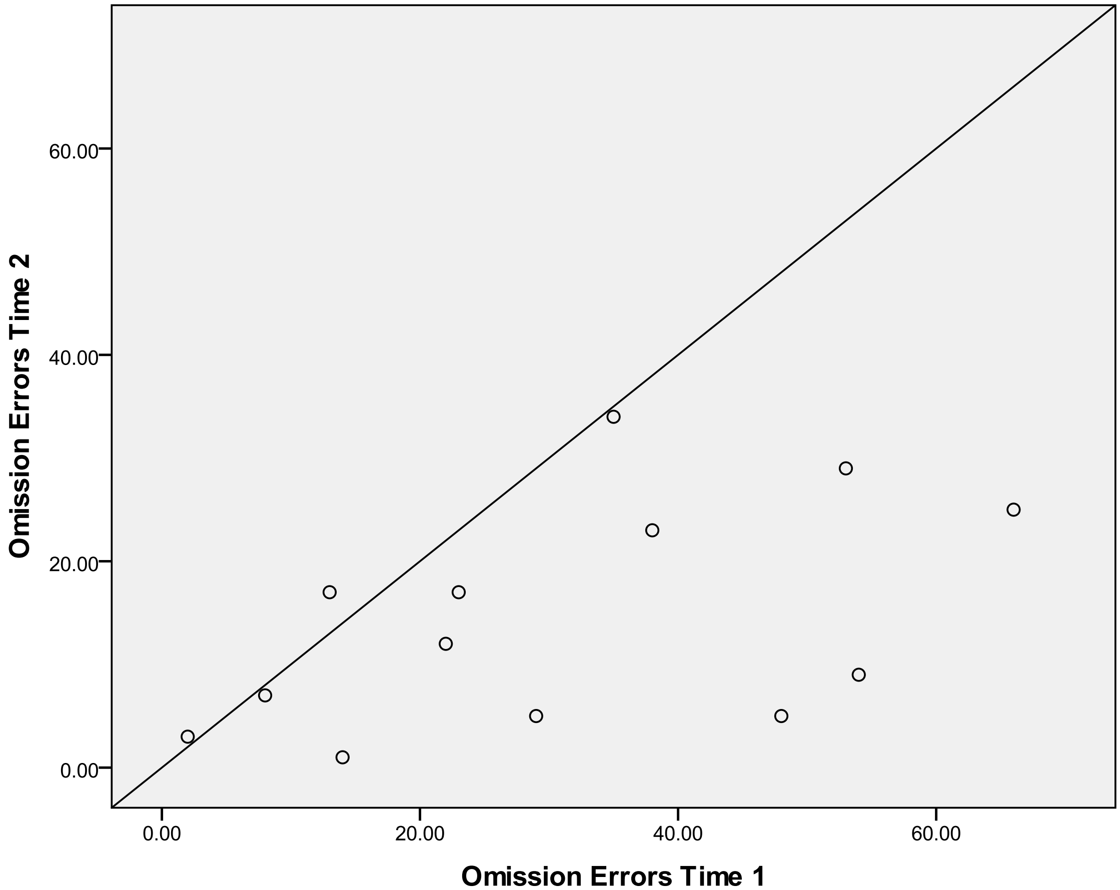

Figure 1. A scatterplot depicting the relationship between pre-intervention and post-intervention assessment of Virtual Classroom CPT Omission Errors.

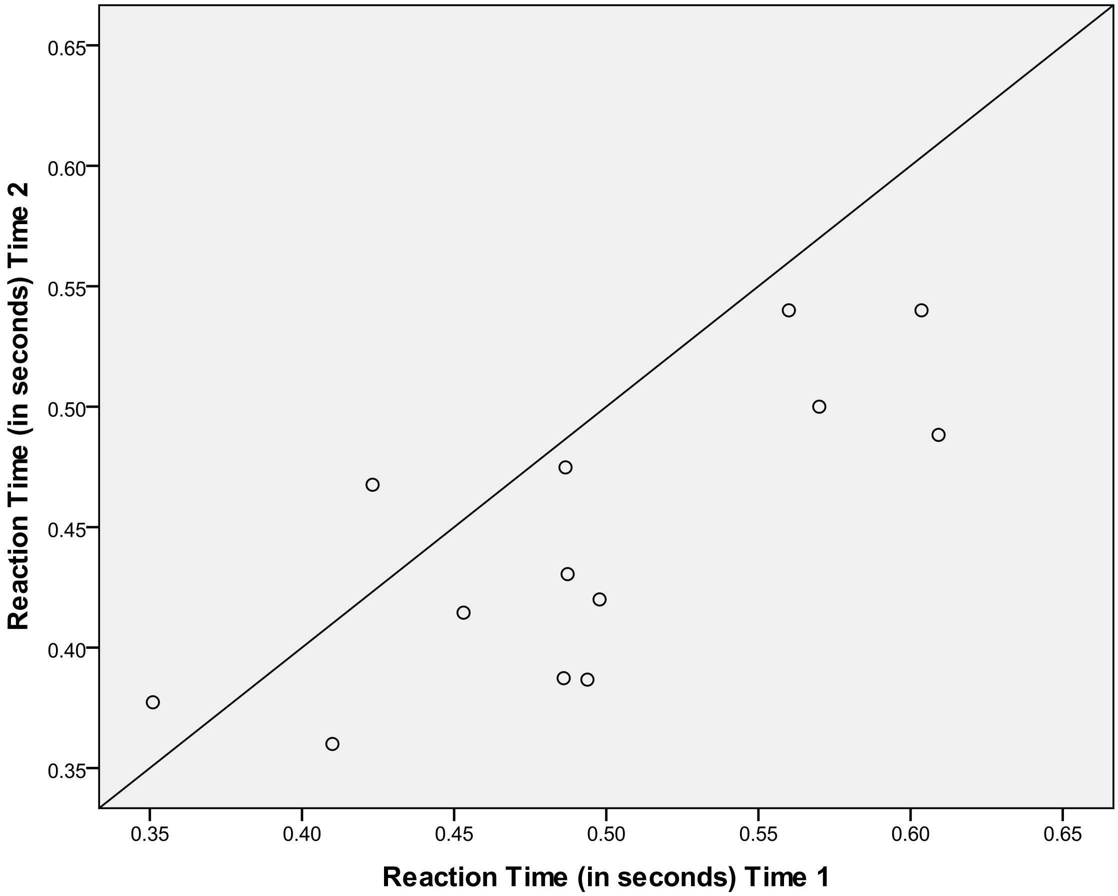

Figure 2. A scatterplot depicting the relationship between pre-intervention and post-intervention assessment of Virtual Classroom CPT Reaction Time (in seconds).

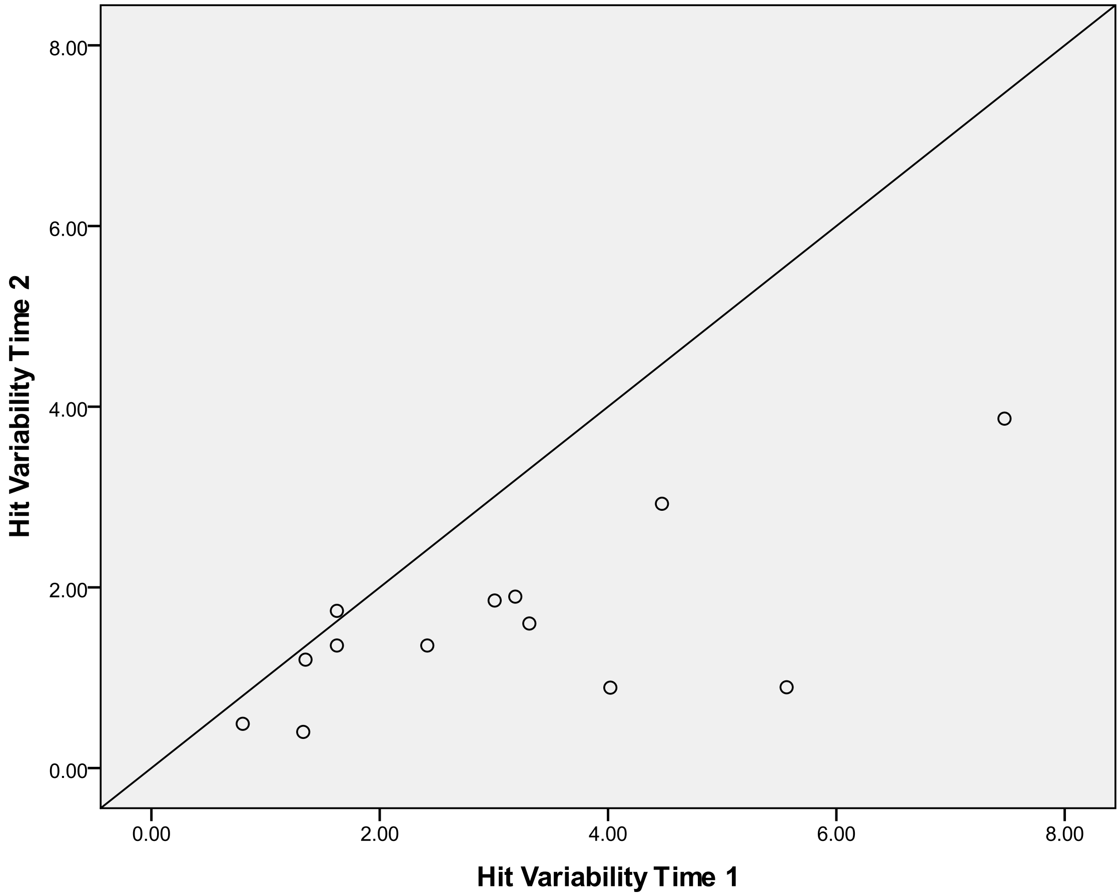

Figure 3. A scatterplot depicting the relationship between pre-intervention and post-intervention assessment of Virtual Classroom CPT Hit Variability.

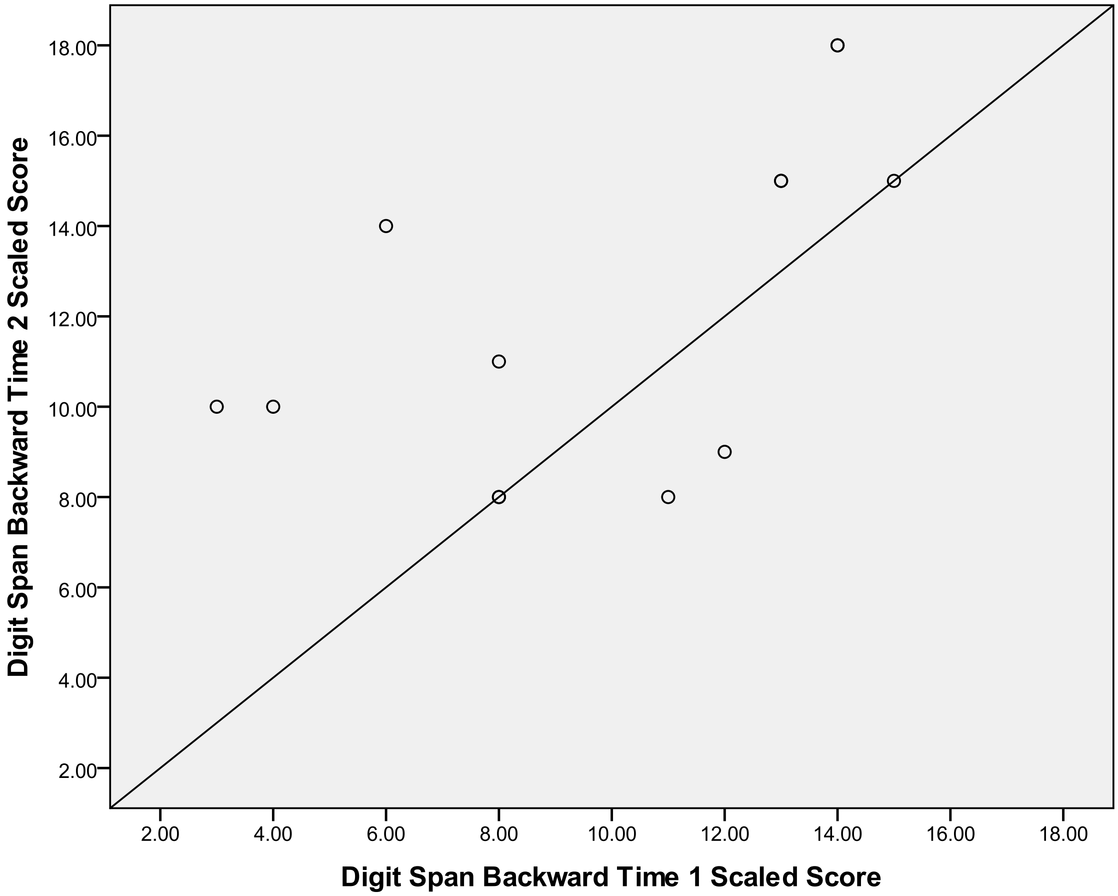

Figure 4. A scatterplot depicting the relationship between pre-intervention and post-intervention assessment of WISC-IV Digit Span Backward (age-corrected scaled score).

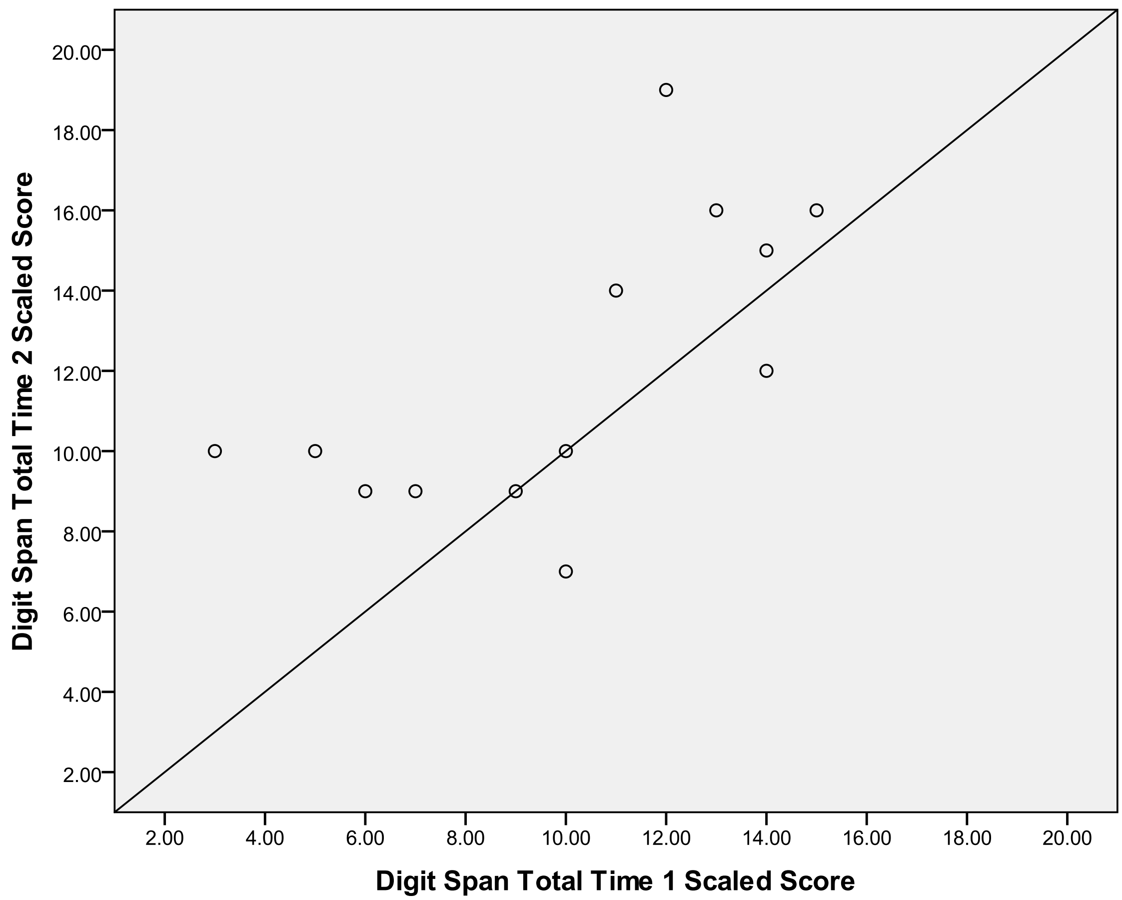

Figure 5. A scatterplot depicting the relationship between pre-intervention and post-intervention assessment of WISC-IV Digit Span Total Score (age-corrected scaled score).

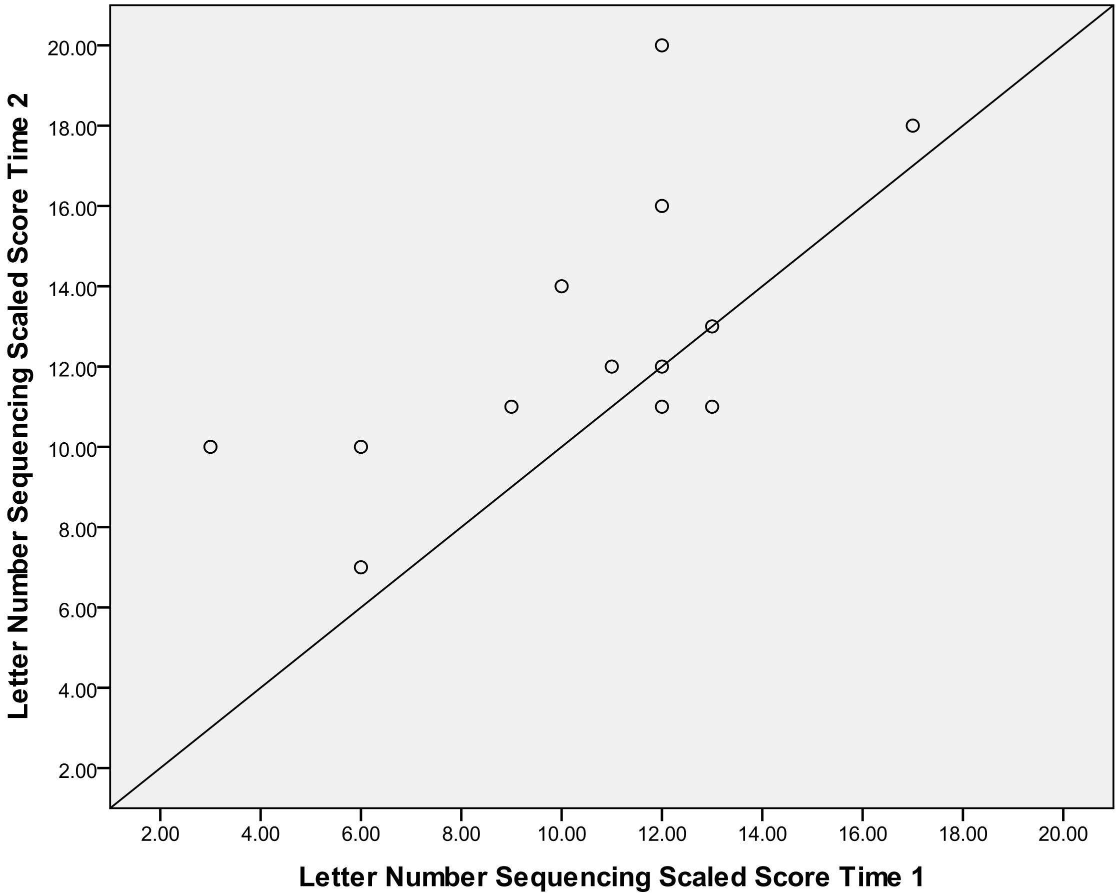

Figure 6. A scatterplot depicting the relationship between pre-intervention and post-intervention assessment of WISC-IV Letter Number Sequencing (age-corrected scaled score).

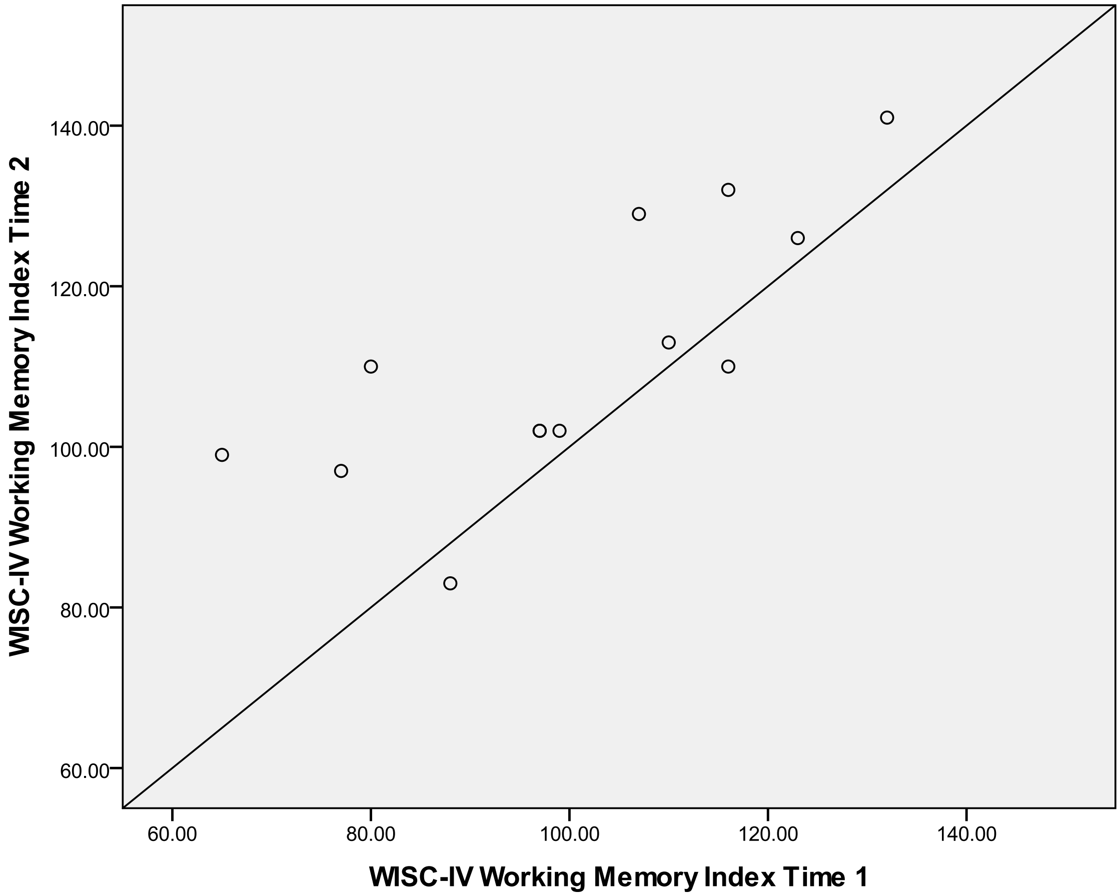

Figure 7. A scatterplot depicting the relationship between pre-intervention and post-intervention assessment of WISC-IV Working Memory Index (age-corrected standard score).

Abstract for *Dissertation Abstracts International*

The role of working memory (WM) in disorders of attention and learning is well established in the literature, some suggesting that low working memory may be a core deficit in AD/HD. As such, computerized cognitive interventions to improve WM have been developed and shown promise by demonstrating training effects such as improved attention and fluid reasoning. However, debate continues as to whether adaptive training leads to improvement on non-trained tasks. Little research has demonstrated improvements that generalize to “real life” WM or attention. The current study examined the effectiveness of WM training on real-world attention performance. Participants included 15 children, ages 6-15, identified as having learning and attention problems. Both before and after completing 5 weeks of WM training, each child was assessed via the Virtual Classroom Continuous Performance Task, a validated measure of sustained attention set within a virtual environment. Results suggested that WM training led to substantial improvements in sustained attention in a real life scenario (classroom learning), as evidenced by decreases in omission errors, reaction time, and hit variability. Observing such improvements on ecologically relevant measures of attention adds to the discussion that computerized WM training may be a viable option to treat attention disorders.

Keywords: working memory, cognitive training, virtual reality, AD/HD, ecological validity, attention

Appendix A

Literature Review

Can Intervention Change the Brain?

Exposing the responsibility of poor working memory in clinical disorders begs the question of whether or not cognitive skills can be improved. Over the past decade, the research base on cognitive training has exploded in volume. New discoveries in the plastic properties of the brain lend promising hope to potential treatments for cognitive disorders. However, the idea that the brain could physically change through development and experience is an old one. For decades, the topic of neuroplasticity has been hotly debated by psychologists across all fields. Whether or not the brain is a fixed structure, remaining anatomically static throughout adult life, has been a discussion of psychologists for over a century. In 1896, George Wilson questioned whether insane mental status was an inheritable characteristic or if, in contrast, the brain may change over time, producing such a result. A year later, Lindley (1897) suggested that plasticity was necessary for a species to adapt to its environment. Early hypotheses on the brain's ability to create or regenerate neurons, called neurogenesis, was largely influenced by the work of neuroscientist Ramon y Cajal who won the 1906 Nobel prize for his model of the structure and connections of neurons. Cajal (1928) hypothesized that the mechanism for learning and development was plasticity of neurons, suggesting that neurons are created and changed throughout development and into adulthood. Initially, this idea was widely rejected as the prevailing view held by contemporary neuroscientists was that an individual is born with a full arsenal of brain cells and, by adolescence and into older adulthood, these cells slowly die and are not replaced. Cajal's findings revealed

prolonged synaptic changes produced by learning that improved efficiency between neurons, even in the adult brain. The plastic property of a neuron's synapse was not formally proposed until 1948 when Konorski asserted that a neuron may be subject to either transient change or enduring plastic change when activated by the right sensory stimuli. This proposal was embedded with an important implication; neurons are active when they change. Donald Hebb (1949) later identified the location of such change; noting that the connection between neurons is strengthened when associatively active. When two neurons in close proximity are associatively active in a repetitive manner, both the pre-synaptic and post-synaptic regions contribute to the induction of lasting cellular changes and associative strength. He writes:

> When axon of cell A is near enough to excite a cell B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased. (p. 62)

As cells that are close in proximity continue to be repeatedly active together, they tend to become associated. To this, Carla Shatz from Stanford University coined the maxim, "Cells that fire together, wire together" as a summary of Hebb's work. In an attempt to compile physical proof of such changes, Lømo (1966) discovered changes in the hippocampal brain regions of rabbits after dissection. He noticed that increased excitation of associated neurons over time led to stronger evoked potentials, a phenomenon which he would call long-term potentiation (LTP). This observation meant that increasing the rate of fire in the presynaptic cell would improve the postsynaptic cell's sensitivity, thus increasing the amount of receptors on that cell's surface and

enacting physical changes to each cell. Since that time, LTP has been used as a theoretical basis of learning, skill acquisition, and adaptation to one's environment.

Learning and Skill Acquisition

Evidence to support experience-dependent changes in the brain is overwhelming. Preliminary research in this realm has focused on sensory and motor learning in animals as a result of developmental exposure or deprivation. This research suggests that unique sensory and motor experience can produce significant and enduring plastic changes in the brain. For example, Hebb (1949) raised puppies in an isolated environment without social interaction, later finding that such conditions produced insensitivity to painful experiences. In the same study, Hebb found that animals raised in the dark later had significantly restricted visual systems. Weisel and Hubel (1963) showed that exposing kittens to monocular deprivation would lead to poor spatial vision. Moreover, a study by Schanberg and Field (1987), in which baby rats were given tactile stimulation (brushing) during development, showed enhanced motor skills and spatial learning in adulthood with correlated changes in cortical organization. Finally, the neural systems involved in working memory were shown to be plastic, in that primates were able to improve on an object recognition task after extended practice (Rainer & Miller, 2000). Such research implies that the developing brain is profoundly shaped by experience, exposure, and environment.

Building on this evidence, the rules and properties of cortical plasticity in the human brain, in response to learning and experience, are being increasingly explained. In their review of the advancements in plasticity research, Buonomano and Merzenich (1998) note that the cortex can preferential allocate neural area based on the most used

input sources, suggesting that repetition and rehearsal in learning can lead to increased area in cortical mapping devoted to that particular skill. Although the mechanisms for plasticity have been widely studied, early research on the effects of cognitive training offered little support in the way of explaining enduring neuronal and behavioral changes. The first of such studies, conducted by Butterfield and Wambold (1973), examined whether short-term memory could be improved by subvocal rehearsal strategies. The practice of the skill only led to temporary increases in STM without transfer to everyday performance. Kristofferson (1972) also evaluated the benefit of prolonged rehearsal on a character-classification task. She found that those who had practiced the task were not able to conduct the character comparisons with any more efficiency than those who did not have extra practice. Even more, they took similar time to process the classifications, indicating that the capacity for holding previously practiced trials did not increase. Yet memory has, in fact, been shown to improve after practice. Ericcson, Chase, and Faloon (1980) discovered that a subject was able to recall 79 digits after practice by grouping numbers in association with material from long-term memory. However, when asked to repeat a series of letters, he was only able to recall a string of six. This finding illustrates the highly-material specific nature of rehearsal strategies; suggesting that an individual is expected to improve on a practiced skill. In the case of Ericcson's subject, his overall working memory capacity was not improved.

Isolated cognitive domains have been the primary target for intervention through various rehearsal strategies and repetitive skill building exercises. For the treatment of AD/HD, numerous attentional process training (ATP) programs have been created to improve attention and executive functioning with substantial research demonstrating their

effectiveness. For example, Kerns, Eso, and Thompson (1999), authors of the attention training program *Pay Attention!*, found that their intervention produced improved performance on non-trained attention measures and academic efficiency in an experimental group of children with AD/HD simply based on repetition. Tamm and colleagues (2010), also examining this program, found similar results including a decrease in ratings of AD/HD symptoms by parents and clinicians, as well as improvements in standardized measures of fluid reasoning and working memory. Further, the Computerized Progressive Attentional Training (CPAT) program, which targets several dimensions of attention including sustained, selective, and executive attention, has been shown to be effective in reducing inattentiveness rated by parents as well as improving non-trained tasks such as reading comprehension (Shalev, Tsal, & Mevorach, 2007). Thus, evidence supports the efficacy of such training interventions in both improving attention and ameliorating peripheral symptoms of AD/HD. With what is understood about the relationship between working memory and AD/HD, isolating working memory as the domain of interest for intervention appears to be a logical choice.

Computerized Cognitive Training

In the first published study in which Cogmed ™ RM was utilized as the training paradigm, Klingberg and colleagues (2002) employed a double blind, placebo controlled research design to examine differences between two groups in outcome measures of working memory, attention, non-verbal reasoning, and inattention as measured by head movement. The groups consisted of 7 children diagnosed with AD/HD and 7 controls. Participants were initially assessed with a trained-version of a visuospatial working memory task, a non-trained version of the same task (similar to a span board), the Stroop

task, and Raven's Colored Progressive Matrices (Stroop 1935; Raven, 1995). Subsequently, participants were assigned by group to either an intensive and adaptive working memory training program, in which the level of difficult depended on performance of the participant, or an easy and static program that did not vary by difficulty. Further, the experimental group receiving the graded training also trained at length each day; at least 25 minutes over 5 weeks. Improvements in working memory capacity were evident for the experimental group in both trained and non-trained working memory tasks. Interestingly, the experimental group also made significant gains in non-verbal reasoning ability and significantly decreased head movements in the follow up assessment. Group differences were observed on both WM tasks, Stroop Accuracy, Raven's Progressive Matrices, and number of head movements. This pilot study documents the initial evidence that explicit working memory training may improve other domains secondary to working memory capacity.

Klingberg and his team (2002) also hypothesized that healthy adults who trained working memory in the same structured paradigm would also see improvements in similar areas of cognition, proposing that deficits were not a pre-requisite to improving WM capacity. 4 healthy adults participated in the intensive and adaptive training and, as expected, improvements in spatial working memory, reaction time, and non-verbal reasoning were evident at follow up testing. The healthy adult group also significantly outgained the placebo group of children. The findings illustrated the dynamic, plastic properties of cognition and the ability for even healthy individuals to benefit from such training. Moreover, benefits from WM training could transfer to other domains.

In a follow up study to the pilot, Klingberg et al. (2005) increased the sample size of the experimental group, including 53 children diagnosed with AD/HD who were not taking stimulant medication. Although the researchers could expect a general increase in working memory capacity by extrapolating results from the previous study, it was of interest if children receiving the training would show a decrease of classic AD/HD symptoms and thus a parental rating scale of AD/HD behaviors was used as an additional outcome measure. Similar to the pilot study, significant improvements were observed in both trained and non-trained tasks. Working memory capacity, both the span board and digit span measures, time to completion on the Stroop task, and non-verbal reasoning, as measured by Raven’s Progressive Matrices, improved after training. More importantly, significant reduction of AD/HD related behaviors, including inattentiveness and hyperactivity, were observed in parent ratings. However, teacher’s ratings on the same measure were not different after training. Additionally, the researchers observed the participants to maintain increases in working memory capacity and secondary domains at a three month follow up, indicating that training gains could be expected to hold over time.

Neurobiological Evidence for Improvements After Training

To evaluate potential neurobiological changes after working memory training, Oleson et al. (2004) conducted two studies in which participants underwent fMRI imaging before and after training. In the initial study, only three healthy adult subjects were used. Subjects were scanned while doing several working memory tasks twice before and once after training. Comparisons of brain activity before and after training revealed specific regions with increased activity; the right middle-frontal gyrus, the right

inferior parietal cortex, and bilaterally in the intraparietal cortex. To confirm and support results of the initial study, the team increased the number of participants to eight. The second experiment utilized a similar design and scanned each subject five times, resulting in similar significant increases in the frontal and parietal areas of the cortex and, additionally, the thalamic and caudate nuclei. The authors noted that these findings were contrary to earlier research that has found practice-related decrease in brain activity (Raichle et al., 1994). It was proposed that differences in changed activity may be attributed to the adaptive training paradigm implemented by new WM training programs that demands on-line attention focused on unique stimuli. In the previous study, the training paradigm relied on priming and automation; potentially increasing efficiency of learning and thus decreasing brain activity. The implication of the Oleson et al. (2004) finding is that higher brain activity in the frontal and parietal cortical areas is positively associated with higher working memory capacity and that such change, as induced by training, points to underlying cortical plasticity.

Despite evidence to support an effect of training on cortical plasticity, little attention has been given to neurochemical changes related to cognitive training. To remedy this, McNab et al. (2009) examined changes in dopaminergic functioning in individuals who received working memory training. Relying on previous research which has implicated cortical release of dopamine during a working memory task, McNab and colleagues identified both D1 and D2 dopamine receptors as potentially regulating dopamine function required for intensive cognitive tasks. Thirteen healthy males participated in the adaptive working memory training paradigm for roughly 35 minutes a day over five weeks. Significant increases in WM capacity was observed following

training. Before and after training, the binding potential of D1 and D2 dopamine receptors was measured with positron emission tomography (PET). Additionally, fMRI scans had been conducted on each subject to locate the areas of cortical change and identify potential areas of neurochemical influence. Each region of interest was measured for receptor binding potential and was compared to baseline measurement. The results showed that training-related changes in WM capacity were significantly correlated to changes in D1 receptor binding potential. Further, the association was negative; indicating that larger decreases in binding potential were related to larger increases in WM capacity. No relationship between training gains and D2 binding potential was found. It should be noted that the relationship between dopamine binding potential was nonlinear and U shaped, meaning that an optimal amount of dopamine was needed for best possible performance. The authors concluded that "…the changes [may] reflect long-term adjustment of the concentration of D1 receptors in response to a prolonged increase in the level of endogenous dopamine during WM training" (p. 802). Further, the findings corroborate previous research that observed a negative correlation between D1 receptor density and WM capacity in patients with schizophrenia (Abi-Dargham et al., 2002). Most importantly, the findings support a strong relationship between WM training and neurochemical plasticity.

Training Effects in AD/HD Populations

In light of the initial findings that working memory training leads to improved performance on non-trained tasks, such as measures of non-verbal reasoning and executive functioning (e.g. Klingberg et al., 2002), new research has sought to replicate these findings and demonstrate that an increase in working memory capacity may have

significant effects on other cognitive domains, potentially leading to the improvement of symptoms in clinical disorders of cognition. Due to the known presence of working memory deficits in children with AD/HD (Barkley, 2006), several such studies have examined the effect of WM training in this population. Beck et al. (2010) identified an experimental group of 49 children with AD/HD who received the adaptive, 5-week WM intervention program; hypothesizing that training would ameliorate executive dysfunction, inattention, and other AD/HD related symptoms as measured by parent and teacher ratings. A control group also completed baseline and follow up testing, but received a non-adaptive and much less difficult version of the WM training program. This group was waitlisted for treatment and later received the adaptive intervention. All participants completed baseline, post-training, and 4 month follow up evaluation in several different domains; including parents and teacher ratings of AD/HD symptoms, executive functioning and working memory capacity. A comparison of groups revealed significant differences in post-training outcome measures, indicating that the experimental group made greater improvements in several areas. First, the experimental group was rated by parents as displaying less inattention and hyperactivity after training. Additionally, parents rated the experimental group as having improved working memory, planning/organization, initiation, and overall meta-cognition. It was observed, however, that teacher ratings did not significantly differ between groups on either AD/HD or executive functioning measures. The authors concluded that the teachers were unbiased and blind to which children received the treatment, implying that an expectancy effect for parents may have contributed to significant changes in rating. At a 4 month follow up, the experimental group continued to display greater improvements on parent ratings in all

outcome measures, but teacher ratings remained unchanged. Further, the control group later received the adaptive WM intervention after follow up and also significantly improved on parent ratings of inattention, but not on ratings of executive function. Similar to the experimental group, teacher ratings did not significantly improve for the control group after receiving the treatment. It should be noted that the working memory training implemented in this study was conducted at the participant's home, unlike the initial research designs of Klingberg and his research team (2002, 2005) who conducted the training in a laboratory setting.

In a similar study, Holmes and colleagues (2010) examined the impact of both intensive working memory training and medication in children with AD/HD. Differing from the initial research on WM training in AD/HD populations that measured training effects in a non-medicated sample, this study was unique in that it compared the effects of training in children both on and off stimulant medication. Additional analyses examined each component of WM (visual or verbal) to better identify the effect mechanism of both training and medication. Twenty five children ages 8-11, diagnosed with AD/HD and receiving prescribed stimulant medication, completed a pre-training assessment battery (off medication) comprised of several verbal and visual working memory tasks (Automated Working Memory Assessment; Alloway, 2007). Additional pre-training assessments comprised of alternative working memory measures were also conducted while the participant was on the prescribed medication; providing an opportunity to compare training gains to medication alone. In line with the author's hypothesis that training effects would be as strong as medication in improving performance on working memory tasks, results yielded significant improvements in

scores directly after WM training, as well as maintained at 6 month follow up. More specifically, training led to greater gains in WM than medication alone. Significant effects of training were observed for both verbal and visual WM tasks; however, performance on visual WM tasks showed greater improvement. Although medication alone did, in fact, improve WM performance, only gains in visual WM were observed. The authors also observed that, “Significant and substantial improvements [from training] were found in all assessed aspects of WM, in each case taking the group from a level below average to one within the average range of scores for children their age” (p. 7). In other words, such dramatic improvements elevated children with identified WM deficits to on par with the ability of their normal peers. An alternative explanation, in which the intense and prolonged nature of the program may facilitate the development and creation of working memory strategies, was also proposed. Such strategies may enhance attentional abilities, leading to improved encoding. The authors concluded that the findings, in support of the efficacy of WM training, may best be used to better understand the differences between verbal and visual WM; indicating that, although medication is helpful in increasing visual WM performance, intensive and adaptive training is useful in targeting the verbal WM systems that account for much of one’s WM functioning in everyday life.

Mezzacappa and Buckner (2010) designed a study in which computerized working memory training was be implemented as an intervention in a school for high risk youth. Citing research that has demonstrated the heightened risk of impoverished children in developing AD/HD (Buckner, Mezzacappa, & Beardslee, 2009), the investigators examined whether intensive training may lead to a reduction of AD/HD symptoms in the

classroom. Eight economically disadvantaged children were enrolled in, and completed, the WM training program that was administered on the campus of the school. Each participant was assessed before and after training by teacher ratings of AD/HD behaviors and standardized measurement of working memory capacity (both visual and verbal). After completing the training, the participants displayed improvements in both verbal and visual memory, improving performance by 36% and 33%, respectively. Teacher ratings of AD/HD behaviors also declined by an average of 26%. Thus, children with previously untreated AD/HD significantly improved behavior in the classroom, benefitting explicitly from working memory intervention. Although its sample size is quite small, the authors note that the importance of this study lies in the participant population, as economically disadvantaged children are far less likely to receive pharmacological intervention for AD/HD (Buckner & Bassuk, 1997). As these children may not have access to medication, WM training appears to be a promising alternative. Further, this study design was unique in that it was the first to conduct the training in the classroom; potentially signifying viability in offering Cogmed ™ -RM as a school-based intervention.

In response to the documented success of computerized cognitive training in AD/HD populations, and continuing to scrutinize the components of working memory that appear to be deficient in AD/HD, Gibson and colleagues (2011) conducted a component analysis of working memory training. They stated, although it is assumed that WM training alleviates deficient WM capacity in AD/HD, "…there has been no attempt to determine whether the components of WM that are enhanced following adaptive training are the same components that are deficient before training" (p. 3). Using the dual-component model of working memory (Unsworth & Engle, 2007), which posits that

WM can be divided into primary memory (PM) and secondary memory (SM) factors, the authors examined the mechanism of action for cognitive training, hypothesizing that a simple span training methodology would target the PM component of working memory only. Participants included 47 adolescents, between the ages of 11 and 16, that had been given a diagnosis of AD/HD and were on a medication regimen. Subjects were randomly selected into two groups; one group receiving verbal WM training, and the other group receiving visual WM training. Employing an immediately free recall task (list learning) that allows for distinction of PM and SM processes by calculating the probability of correct recall for the item's serial position, the authors were able to analyze which component, PM or SM, showed greater improvement after training. Assessments were conducted at both pre and post training and compared. The authors found that, for both visual and verbal conditions, accuracy for recall was significantly higher after training, but only for the most recent portion of the list, thus suggesting that simple span training only enhances the PM component of working memory. This is significant in that recent component analysis of WM deficits in AD/HD have revealed that only recall from SM is impaired (Gibson et al., 2011). Therefore, it was argued that this form of WM training may not be entirely appropriate for the treatment of WM deficits in AD/HD populations. The authors concluded that benefit of improved working memory capacity via WM training should be viewed to operate through compensatory pathways, suggesting that improved PM may "reduce the burden on deficient SM processes by decreasing the amount of information that is lost from PM thereby decreasing the amount of information that must be recalled from SM" (p. 6).

Transfer of Skills

One major finding across the majority of studies that have employed WM training as an intervention is the transfer or generalization of working memory capacity to other domains of cognitive functioning and behavior. As evidenced by basic findings in the learning and plasticity literature (e.g. Ericcson, Chase, and Faloon,1980), practice of any skill should result in improvement of that skill. As is such, it is not surprising that the intensive and adaptive training of working memory would lead to increased working memory capacity. However, the literature base is growing to support the idea that explicit training of working memory may lead to improved skills in other domains and generalized improvements in everyday functioning. For instance, Dahlin (2011) explored the effectiveness of WM training on reading performance in an academic setting. She hypothesized that children with special needs, specifically attention and learning problems, would display improved reading comprehension after training. Previous research has demonstrated that the development of reading comprehension relies heavily on working memory capacity (Cain, Oakhill, & Bryant, 2004), thus offering an appropriate skill in which to predict transfer. Similar to the design by Klingberg and team's (2002) initial study, 41 children, ages 9-12, were assessed in the areas of working memory, non-verbal reasoning, and aspects of executive function (i.e. response inhibition) before receiving the intervention. Assessment data from a control group (used from Klingberg's pilot study) who were given the placebo version of the training which did not adjust to participant's ability level was used for comparisons. Additionally, the children's reading ability was measured in three sub-domains; comprehension, word decoding, and orthographic knowledge. The analysis of post-training assessment yielded

encouraging results; the experimental group had significantly improved in reading comprehension with an effect size of .91, and maintained that improvement at a later follow up (6 months) while the control group did not show improvement. Corroborating findings of earlier studies, the experimental group also significantly improved in working memory and non-verbal reasoning measures after training. No significant changes in decoding or orthographic skills were noted. More specific analyses demonstrated a correlation between reading comprehension and working memory capacity. This study is important because, as the author notes, reading dysfunction is often resistant to treatment and children with such problems, unless receiving extremely early intervention, can fall behind quite quickly. Further, the proposed reason behind the "treatment-resistant" dilemma in reading is that working memory is often low (Howes, Bigler, Burlingame, & Lawson, 2003). Thus, working memory intervention may serve as a supplemental treatment; part of a holistic approach to component and comprehension deficits.

In an attempt to further evaluate the educational significance of working memory training, Holmes et al. (2009) identified three areas of concern: a) do training benefits extend to non-AD/HD children with WM deficits, b) which WM components are trained, and c) can an increase in WM capacity, via training, serve to sufficiently overcome learning problems associated with low WM? To address these questions, they sampled 22 children (12 boys) to complete the intensive and adaptive WM training and 20 children (15 boys) were selected to receive the placebo (non-adaptive) version. Each child's verbal and visual working memory was assessed prior to training. The *Automated Working Memory Assessment* (Alloway, 2007) was used, offering several additional subtests designed to tap into unique working memory activities untrained in the WM

intervention. For instance, one subtest called for the participant to follow multi-step instructions; *"Touch the yellow pencil and put the blue ruler in the red folder."* The authors of the study argued that this pragmatic representation of working memory ability closer approximates what is required of children in the classroom. Using such measures also allowed examination of whether the training gains would extend beyond trained tasks. Each child's reading and math ability was also assessed prior to training. Comparison of pre and post-training assessment revealed significant improvement on all both verbal and visual working memory subtests by the experimental group, while the control group only improved on verbal WM tasks. The authors hypothesized that this finding may be related to the specific subcomponents of WM that are targeted by the training program; most notably the significant role of attention allocation in visual working memory. Further, the training gains made by the experimental group persisted to a 6 month follow up. With respect to changes in reading and math ability as a function of training, neither group showed improvement at the post-training assessment; however, the group that received the intensive and adaptive training showed significant improvement in math ability at the 6 month follow up. This is not surprising; increased WM capacity may take time to manifest itself into academic performance as students utilize this cognitive ability to master the concepts. Thus, the authors' stated, adaptive WM training may have utility in ameliorating expected problems in math in children with low WM. Because 80% of children with WM impairments have substantial problems in either reading or math, or both (Gathercole & Alloway, 2008), this finding is of profound importance to the educational system. Moreover, Holmes and colleagues noted that children who received the training also endorsed improved memory strategies as a result;

many reported developing new strategies to concentrate and rehearse the newly learned information, leading to better retention and use of the material. Computerized cognitive intervention that targets WM may indeed have peripheral benefits that extend outside of simply WM capacity.

Although research findings have strongly supported the application of WM training in academic settings to improve achievement in children, little attention has been given to pre-school age children and the importance of early intervention strategies when evaluating cognitive deficits. To address this issue, Thorell, Lindqvist, Bergman-Nutley, Bohlin, and Klingberg (2009) examined inhibitory control and working memory in pre-school children, hypothesizing that training in these domains would lead to transfer of improved skill to attentional capacity. Inhibitory control, an important function of the executive system, has been shown to be strongly correlated with working memory (Engle & Kane, 2004). As is such, pre-school age children appear more challenged by the demands of inhibitory control than working memory, offering a more appropriate domain to train in this population. Groups of preschoolers were assigned to either working memory or inhibition training group and compared to a control group of peers who received a non-adaptive and simple video game. The current study differed from previous research on WM training in several ways due to the limitations of pre-school children and the introduction of a new training domain. Instead of reducing AD/HD symptoms by training WM, the current study used pre-school children with no formal diagnosis of any disorder. Further, children only trained for 15 minutes a day as opposed to the intensive 30-45 minutes utilized in studies with similar design. The children assigned to the inhibition training group completed a training task of inhibitory control within a go/no-go

paradigm. To assess for improvements after training, each child was given measures of working memory (visual and verbal), auditory attention, inference control, response inhibition, and perceptual reasoning before and after the training. As expected, participants in both the WM and inhibition training groups improved on the respective trained task. Analyses of outcome measures revealed greater improvements than controls on non-trained working memory and auditory attention tasks for participants in the WM training group, while the inhibition group did not show any greater improvement than controls on non-trained tasks of inhibitory control. This finding is important in two ways: first, the study demonstrated that pre-school aged children could benefit from WM training and experience gains in non-trained tasks; and second, the training of inhibition did not yield better outcomes than a control group aside from expected improvements on trained tasks. Further, the WM training program used by Thorell and colleagues (2009) only contained visual WM exercises whereas previous versions had included a mixture of both verbal and visual. Even so, the explicit training of visual working memory led to improvements on non-trained verbal WM measures. The authors concluded that, “the transfer effect…which is in line with previous neuroimaging findings showing evidence of supramodal WM areas (i.e. areas that are active irrespective of the type of stimuli being held in WM)” (see Hautzel et al., 2002).

Utility in Other Populations

With the surmounting empirical success of WM training, despite being in an early stage of research, curious investigators have begun to identify specific populations, other than children with AD/HD, in which WM has the potential to be an effective target of cognitive intervention. In the first study aimed at a clinical population of adults,

Westerberg and research team (2007) conducted a pilot study to examine whether individuals who have suffered a stroke may benefit from WM training. Stroke-induced cognitive impairments, particularly working memory, can be profound and persistent; leading to severely diminished daily functioning and quality of life. Previous research on cognitive training in a brain injured population has yielded mixed results, with the primary benefits linked to improved attention on standardized measures and self-reported executive functioning in everyday life (see Cicerone, 2002; Sohlberg, McLaughlin, Pavese, Heidrich, & Posner, 2000). In light of these findings, Westerberg and her team utilized both standardized assessment and behavioral ratings as outcome measures, hypothesizing that adaptive working memory training would lead to improvements in both methods of assessment. The study examined 18 individuals (age range from 35-65, 12 males) who had suffered a stroke and were in the chronic recovery stage (12-36 months after injury) at the time of participation. Half of the group received WM training while the remaining participants did not receive treatment. Similar to previous research designs, outcome measures included measures of WM, response inhibition, non-verbal reasoning, attention, and short term memory. Additionally, a self-report measure of perceived cognitive failures was included, where participants rate the severity and frequency of common failures of cognition in everyday life after injury. Results showed significantly more improvement on non-trained measures of WM for the treatment group as compared to the control group. Moreover, the treatment group rated themselves as experiences significantly fewer cognitive failures at post-assessment than did controls. This finding was the first to demonstrate that working memory training in clinical adult populations can lead to symptom reduction; further strengthening the evidence that WM

training gains extend past trained tasks and into everyday functioning. The limitations of this study lie in the passive nature of the control group; that is, it is impossible to rule out that the improvements in outcomes made by the treatment group were entirely attributable to an expectancy effect; a common threat to intervention research.

Further exploring the impact of WM deficits in brain injured individuals, Lundqvist, Grundstrom, Samuelsson, and Ronnberg (2010) examined whether WM training could improve functional outcomes and performance on complex WM tasks. The sample included a heterogeneous group of individuals with traumatic brain injury, stroke, or other cerebrovascular accident with self-reported WM deficits and an impaired WM index score as measured by the WAIS-III (Wechsler, 1997). Participants were given a baseline assessment before training consisting of simple, trained WM tasks as well as more demanding complex WM tasks that require both storage and manipulation processes during encoding. Four weeks after training, participants showed improvement not only on trained tasks but also non-trained tasks of auditory attention, complex spatial working memory, and inhibition, suggesting significant transfer of skills to related cognitive domains. These improvements persisted through a twenty week follow up assessment. Additionally, functional outcome measures were administered to examine whether self-reported quality of life, overall health, and perceptions of WM activity in everyday life had improved after training. The latter was assessed by identifying several typical problem areas for individuals with brain injury; community management (finances, dealing with authorities), household management (shopping, cooking), and socialization (conversing with multiple persons). Results of a four week follow up showed significant improvement in participant's ratings of their own occupational

performance in these domains, indicating an effect of training in everyday cognitive functioning. The authors anecdotally noted that at a meeting conducted twenty weeks after training, the participants reported feeling “more alert and that they could resist distraction from irrelevant stimuli better in situations without noise. For example, this improvement was noticeable when helping children do their homework, remembering codes and phone numbers, following a road description, and shopping” (p. 1181).

The observable effects and impact of WM training in everyday life continue to be examined by the likes of Johansson and Tornmalm (2011) who similarly identified brain injured individuals as a group with extraordinary potential to benefit from such training gains. This research design examined the effect of training on outcome measures similar to other research on cognitive training in brain injury, including the Canadian Occupational Performance Measure (CPOM; Law et al., 1994) and Cognitive Failures Questionnaire (CFQ; Broadbent, Cooper, Fitzgerald, & Parkes, 1982). The study targeted brain injured individuals with severe cognitive deficits who obtained a FSIQ of <70. These individuals have been typically excluded from previous research on cognitive training as investigators seem to assume that individuals with severe impairments may not benefit from WM training. Nonetheless, the intervention combined WM training with additional peer support from other participants who were training (30 min/day) and education from research staff pertaining to WM functioning in everyday life which facilitated internal and external coping strategies. These additional treatments have not been included in previous studies. After treatment, participants showed marked reduction in the number of cognitive problems endorsed on the CFQ and exhibited improvement on occupational performance. This also led to greater participant satisfaction with such

performance. The authors also demonstrated that participants significantly improved in the level of self-awareness surrounding WM problems. This was evident in a semi-structured interview conducted after training as well as a daily entry into a journal compiled during the training phase. Participants endorsed improvement in areas such as remembering names, sequencing multistep activities, planning, less need to re-check work, and overall self-confidence. However, it should be noted that statistical analysis was not performed on qualitative data and the authors did not report the frequency of such improvements across the sample, simply that these observations had been made. This study is nonetheless important in that it reports on specific areas of training transfer in daily activities; most of which require complex working memory, executive functioning, and meta-cognition. Moreover, it demonstrates that WM training may be viable for a population with severe cognitive deficits rather than simply high functioning individuals with subtle impairments.

Older Adult Populations

Research in the field of cognitive training has just begun to explore the efficacy of such interventions with older adults. With what is known of cognitive changes in older adulthood, with marked changes in working memory capacity being common (Braver & West, 2008), this population stands to gain mightily from advancements in this field. Existing studies have shown the transfer of gains through cognitive training in older adults to be smaller than that of younger adults using the same protocol (Schmiedek, Lovden, & Lindenberger, 2010), suggesting that age may be an important factor in predicting positive transfer to other cognitive domains. However, many of the training methodologies that were employed in previous studies of older adults were non-adaptive;

a characteristic of training that is thought to be vitally important in the quality of outcome. Further, computerized training may introduce an extraneous variable that differentiates the older adult group based on technological savvy instead of actual cognitive ability. Finally, research has demonstrated the reduced plasticity of the brain in older adulthood, making it more difficult for training, which fully depends on neurobiological changes in the brain, to be effective in older adults (Noack, Lovden, Schmiedek, & Lindenberger, 2009).

Richmond, Morrison, Chein, and Olson (2011) investigated these issues in older adults using a WM training paradigm introduced by Chein and Morrison (2010) that was similar to existing WM interventions in that it was intensive and adaptive but did not provide a coaching and interpersonal support structure. The authors do not give clear indication of other components in the training regimen other than the described WM computer tasks. It was unclear if feedback, reinforcement, or rewards were provided. Two groups of older adults were assessed before and after training with one group receiving the computerized training whereas the control group was asked to do basic trivia games on the computer. Subjects receiving the intervention did not improve digit or spatial span but did improve on reading span and also decreased number of repetitions on the CVLT (the authors suggested this finding suggested improved inhibition). However, most measures did not reveal improvement in trained tasks or transfer to non-trained tasks. Even more importantly, this study revealed an alarmingly substantial subjective effect of expectancy. Both training groups equally self-reported improvements in everyday memory. The adaptive training group did, however, endorse better perceptions of attention in real life after the training. This finding highlights an important aspect and

limitation of studies on WM training; the expectancy effect of intensive training, in addition to general exposure such as feedback from testers and increased level of cognitive challenge, has yet to be parsed out of controlled findings. Such effects related to the task environment must be disentangled from true cognitive enhancements using active control groups.

In a similar study, Brehmer and colleagues (2011) examined the efficacy of WM training in an older adult population. 12 participants received the adaptive version and 11 received placebo. All participants received pre-training assessment of trained tasks, including span, but also non-trained tasks such as attention (PASAT), episodic memory (RAVLT), and non-verbal reasoning (Ravens). Most importantly, the authors sought to identify areas in which brain activation changes could be observed using fMRI during a working memory task. Both groups showed general decreases in activation in the inferior frontal gyrus, anterior cingulate, and lingual gyrus of the occipital region. The adaptive training group showed great decreases in activation in the dorsolateral prefrontal cortex, superior temporal region, and lingual gyrus than control group. Further, those who improved the most in WM capacity during training also showed the most decreases in activation in memory and attention-related brain areas. These findings suggest that improvements from training may allow the trainee to use less effort and attention in mental processes in working memory-demanding tasks. Reduction of activation, in this sense, relates to efficiency of neuronal firing throughout these networks.

Brehmer and research team (2012) increased the sample size from their previous examination of WM training with older adults, this time comparing effects of training to younger adults in a similar design. 29 younger adults and 26 older adults were randomly

assigned an adaptive version of WM training whereas similar groups of controls received the low-level practice version. Trained and non-trained working memory tasks, in addition to both near and far transfer tasks, were given as pre and post assessment measures. Participants also rated perceived cognitive functioning in daily life before and after training. Overall, the adaptive training group made significantly greater gains in both criterion and transfer tasks than the placebo group. Results also indicated that young adults showed higher working memory performance both before and after training with larger gains in WM capacity than older adults. However, although this is to be suspected with what is known of the effect of age on both WM and plasticity, younger adults demonstrated greater training gains in certain criterion and transfer tasks, including the Span Board. Further, although younger adults showed greater gains in working memory capacity than older adults during the first week of training, older adults were able to show similar gains by the second weeks. With respect to far transfer, the adaptive training group demonstrated larger performance gains on a task of sustained attention (PASAT; publisher citation), and reported fewer cognitive failures in everyday life. Both adaptive and control group improved equally on tests of inhibition and fluid reasoning; attributed to practice effects by the authors. Finally, training effects were maintained at a 3 month follow up. This study highlights the potential viability of working memory training in older adult populations while also corroborating evidence from previous research demonstrating that younger adults show greater benefit from training (e.g. Schmiedek et al., 2010).

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Appendix B

Human Subjects Review Committee Approval Letter

HUMAN SUBJECTS REVIEW COMMITTEE

CONFIDENTIAL

October 19, 2010

HRSC#: a5/10.104

Sarah DeBoard Marion, PhD
180 N. Oakland Ave.
Pasadena, CA 91101

Dear Dr. Marion:

This letter is to inform you that the Human Subjects Review Committee at the Fuller Graduate School of Psychology has reviewed your research proposal:

The effectiveness of working memory training on virtual classroom performance in children with learning and attention problems

After undergoing the review process, your project has been found to meet the criteria for the ethical treatment of human subjects in research. However, the reviewer on your project is suggesting some minor corrections to the informed consents and assent (please see attached documentation for details).

After you update the proposal, please upload the updated documents into the system as part of the same package (the study will be unlocked, please don't create a new package). The changes should be highlighted in gray and should be submitted no later than October 25, 2010. The HSRC office will review the revisions and provide you the stamped documents that need to be used in the recruitment process.

The project is hereby approved contingent upon submission of the suggested changes.

Your project approval is good for exactly one year from the date on this letter. It is your responsibility to submit an update on your project including data collection status, expected duration of continued collection, and other important information if your project will continue to collect and analyze this data beyond the one-year approval.

Please inform the committee in writing if any substantial changes are made in your research protocol that would affect the treatment of subjects in your research.

Sincerely,

Marta Cenac-Mehedinti
HSRC Manager
Fuller Theological Seminary

Human Subjects Review Committee
Graduate School of Psychology
Fuller Theological Seminary
Approval Date: **October 19, 2010**
Expiration Date: **October 19, 2011**
HSRC Manager initials: **MCM**

cc. Esther Chin, Benjamin Coleman, Rachael Green, Susan Marion

Appendix C

List of Appropriate Journals for Submission

1. *Journal of the International Neuropsychological Society*
2. *Developmental Neuropsychology*
3. *Journal of Learning and Cognition*
4. *Cyber Psychology and Behavior*

Letter of Submission

Benjamin P. Coleman
Travis Research Institute
Graduate School of Psychology
Fuller Theological Seminary
180 North Oakland Avenue
Pasadena, CA 91101

February, 2014

To Whom It May Concern,

I am writing to submit an article entitled "The Effectiveness of Working Memory Training on Classroom-Related Attention" to your journal. This article came about as a result of my dissertation project of the same title. Findings from this project were presented at the annual meeting of the International Neuropsychological Society in February 2013 in Waikoloa, Hawaii.

This is a very important study investigating the relationship between computerized cognitive training and ecologically valid outcome measures. This study demonstrates that working memory training may be effective in improving classroom-related attention for children with learning and attention problems. Implications are discussed regarding the impact of using virtual reality outcome assessment in the evaluation of innovative technology-based interventions.

Thank you for your time. I look forward to hearing from you. Please do not hesitate to contact me if you have any further questions or concerns about this study.

Sincerely,

Benjamin P. Coleman, MA

Appendix D

Curriculum Vitae

Education

Fuller Graduate School of Psychology, Pasadena, CA 2008-Present

Doctoral Candidate

Masters of Arts in Clinical Psychology, 2010

Anticipated (Summer 2014): Ph.D. in Clinical Psychology

Seattle Pacific University, Seattle, WA 2002- 2006

Bachelors of Arts in Psychology, Cum Laude, 2006

Supervised Clinical Experience

Psychology Intern August 2013 - Present

VA Los Angeles Ambulatory Care Center, Los Angeles, CA

Psychology Pre-Intern September 2012- July 2013

Della Martin Center, Huntington Memorial Hospital, Pasadena, CA

Psychology Assessment Clerk August 2011- August 2012

VA Long Beach Health Care System, Long Beach, CA

Psychological Assistant May 2012- Present

Private Practice, Pasadena, CA

Licensed Clinical Supervisor: Mary Rotzien, Ph.D.

Psychology Practicum Intern July 2010- July 2011

Casa Colina Centers for Rehabilitation, Pomona, CA

Psychology Trainee September 2009- June 2010

Fuller Psychological and Family Services, Pasadena, CA

Professional Experience

Clinician August 2008- May 2010

The Center for Neurotherapy, Los Angeles, CA

Forensic Mental Health Clinician January 2007- July 2008

Seattle Mental Health, Seattle, WA

Teaching Experience

Adjunct Professor of Psychology August 2010- Present

Pepperdine University, Malibu, CA

Psychological Testing and Assessment: Fall 2010, Spring 2012, Fall 2012, Spring 2013

Psychopharmacology: Spring 2013

Teaching Assistant March 2011- June 2011

Fuller Graduate School of Psychology, Pasadena, CA

Neuropsychological Assessment

Instructor: Sarah DeBoard Marion, Ph.D.

Professional Presentations and Published Abstracts

Coleman, B., Green, R., Rizzo, A., Marion, S. (2013). *Does working memory training improve virtual classroom attention?* International Neuropsychology Society conference (Waikoloa, HI, February 2013).

Green, R., Coleman, B., Marion, S. (2013). *Working memory training: Does it improve math performance?* International Neuropsychology Society conference (Waikoloa, HI, February 2013).

Young, C., Coleman, B., Green, R., Turnbull, J., Rizzo, A., & Marion, S. D. (2013). *The Virtual Reality Classroom Stroop Task as a measure of executive dysfunction.* International Neuropsychology Society conference (Waikoloa, HI, February 2013).

Thomas, K., Zizak, V., Coleman, B., & Webster, J. (2012). *Neuropsychological performance, effort and pathognomonic signs in veterans with PTSD, brain injury, and controls.* American Academy of Clinical Neuropsychology conference (Seattle, WA, June 2012).

Green, R., Coleman, B., & Marion, S. D. (2012). *Measuring classroom-related inattention in a virtual environment.* International Neuropsychological Society Conference (Montreal, Canada, February 2012).

Coleman, B. P., & Marion, S. D. (2010). *An investigation of reading disability subtypes in interhemispheric function.* International Neuropsychological Society Conference (Boston, MA, February 2011).

Wong, A., Coleman, B. P., Wellman, J., Parsons, T., Rizzo, S., & Marion, S. D. (2010). *Comparison of standardized and virtual environment versions of the Paced Auditory Serial Addition Task.* International Neuropsychological Society Conference (Boston, MA, February 2011).

Wellman, J. N., Wong, A., Coleman, B. P., Parsons, T., Rizzo, S., & Marion, S. D. (2010). *Evaluation of a visual serial addition task in a virtual environment.* International Neuropsychological Society Conference (Boston, MA, February 2011).

Wilson, B. J., Montague, R. A., Kline, F., Coleman, B. P., & Agnor, C. J. (2008).

Attention and academic performance in developmentally delayed boys. Conference of Human Development (Indianapolis, IN, April 2008).

Wilson, B. J., Montague, R. A., Kline, F., Coleman, B., & Agnor, C. J. (2008). *Sustained attention and vagal tone: Relations to the teacher-reported academic performance of developmentally delayed and nondelayed boys.* Conference on Human Development (Indianapolis, IN, April 2008).